Chapter 3
Tainter Gate Design

3-1. Introduction

This chapter presents design guidance for the Corps of Engineers standard tainter gate described herein. The configuration for the standard gate has resulted from much practical and theoretical investigation of alternatives and over 60 years of design and field experience with construction, operation, and maintenance. It is generally the simplest and most economical tainter gate configuration for most applications.

3-2. Geometry, Components, and Sizing

a. Standard Corps of Engineers tainter gate geometry and components.

(1) Primary gate components. The principal elements of a conventional tainter gate are the skin plate assembly, horizontal girders, end frames, and trunnions (Figure 3-1). The skin plate assembly, which forms a cylindrical damming surface, consists of a skin plate stiffened and supported by curved vertical ribs. Structurally, the skin plate acts compositely with the ribs (usually structural Tee sections) to form the skin plate assembly. The skin plate assembly is supported by the horizontal girders that span the gate width. The downstream edge of each rib is attached to the upstream flange of the horizontal girders. The horizontal girders are supported by the end frames. End frames consist of radial struts or strut arms and bracing members that converge at the trunnion which is anchored to the pier through the trunnion girder. The end frames may be parallel to the face of the pier (support the horizontal girders at the ends) or inclined to the face of the pier (support the horizontal girders at some distance from the end with cantilever portions at each end). The trunnion is the hinge upon which the gate rotates. The trunnion is supported by the trunnion girder which is addressed in Chapter 6.

(2) Other structural members. Structural bracing members are incorporated to resist specific loads and/or to brace compression members. Certain bracing members are significant structural members, while others can be considered secondary members.

(a) Horizontal girder lateral bracing. Cross bracing is generally placed between adjacent girders in a plane perpendicular to the girder axes, sometimes at several locations along the length of the girders. This horizontal girder lateral bracing may simply provide lateral bracing for the girders or may serve to carry vertical forces from the skin plate assembly to the end frame. Lateral bracing that is located in the same plane with the end frames is generally made up of significant structural members, while intermediate bracing located away from the end frames provides girder lateral stability and can be considered secondary members. The bracing located in the same plane with the end frames carries significant vertical forces from the skin plate assembly to the end frame and is often considered a part of the end frame (Figure 3-2).

(b) Downstream vertical truss. The downstream vertical truss consists of bracing provided between the downstream flanges of the horizontal girders. Various configurations have been used depending on the gate size and configuration as shown by Figure 3-3. For gates with more than two girders, the downstream vertical truss does not lie in a single plane. Since the horizontal girders are arranged along the arc of the skin plate assembly, the downstream girder flanges do not lie in the same plane. Therefore,

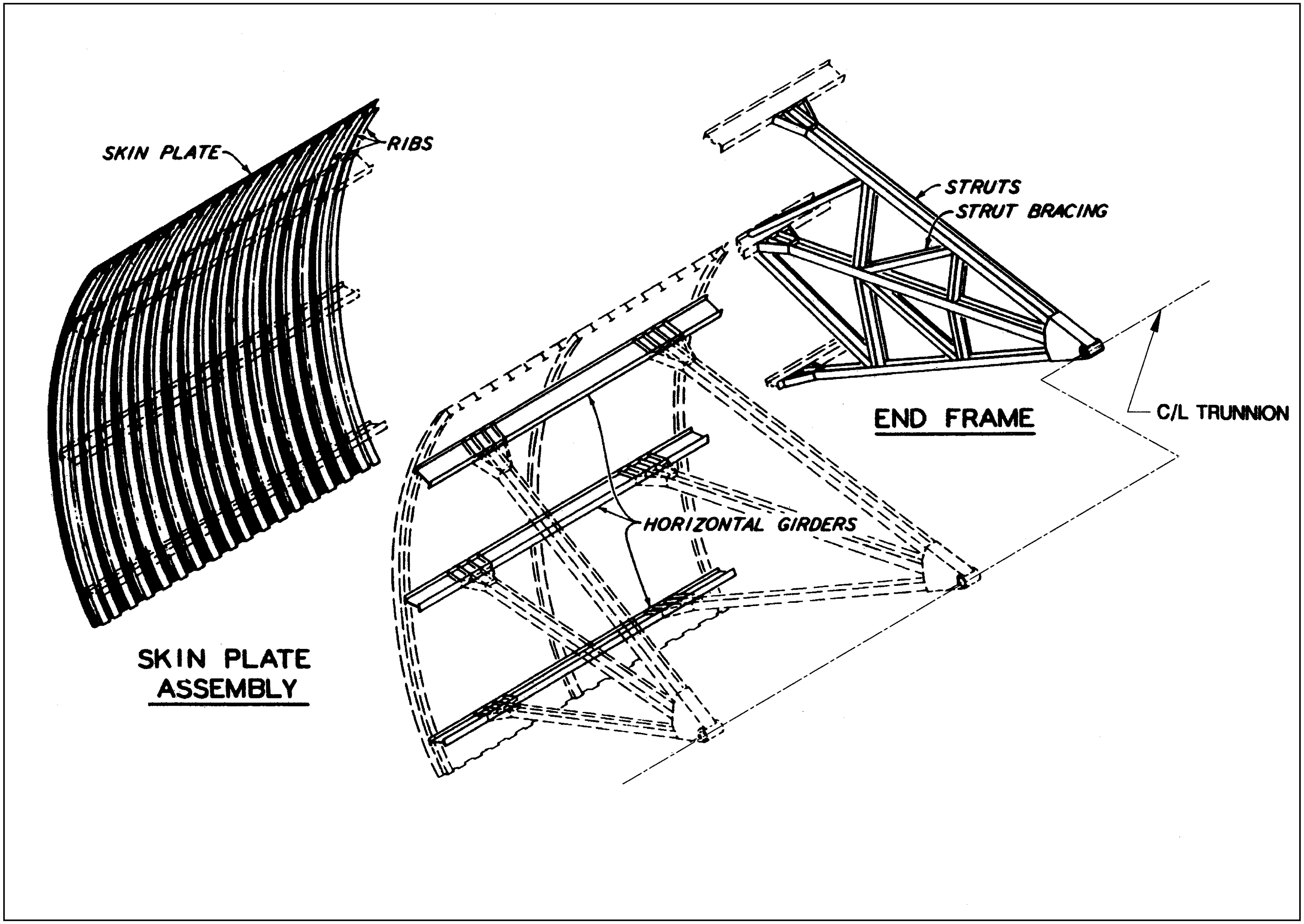


Figure 3-1. Primary tainter gate components

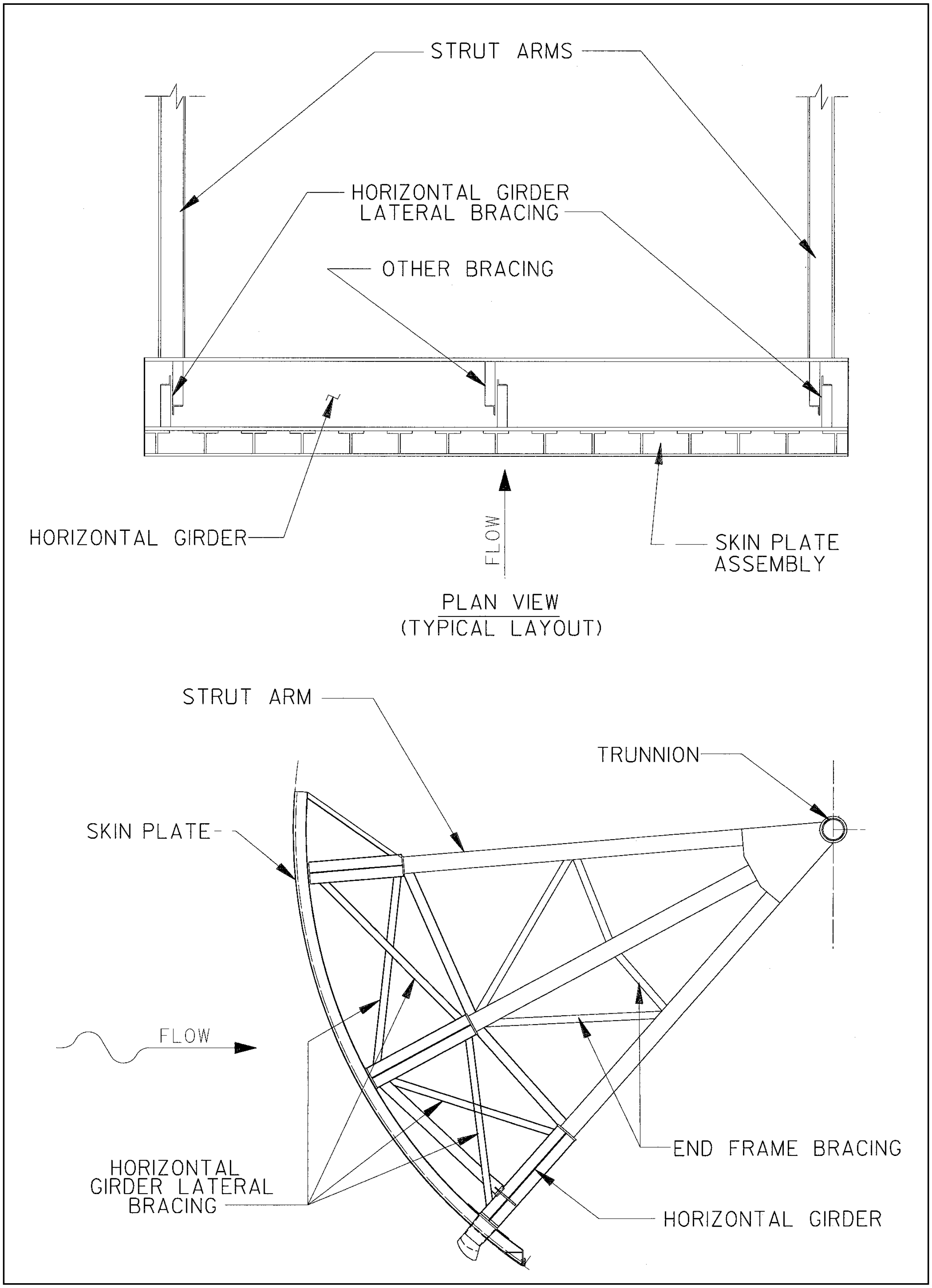


Figure 3-2. Horizontal girder lateral bracing

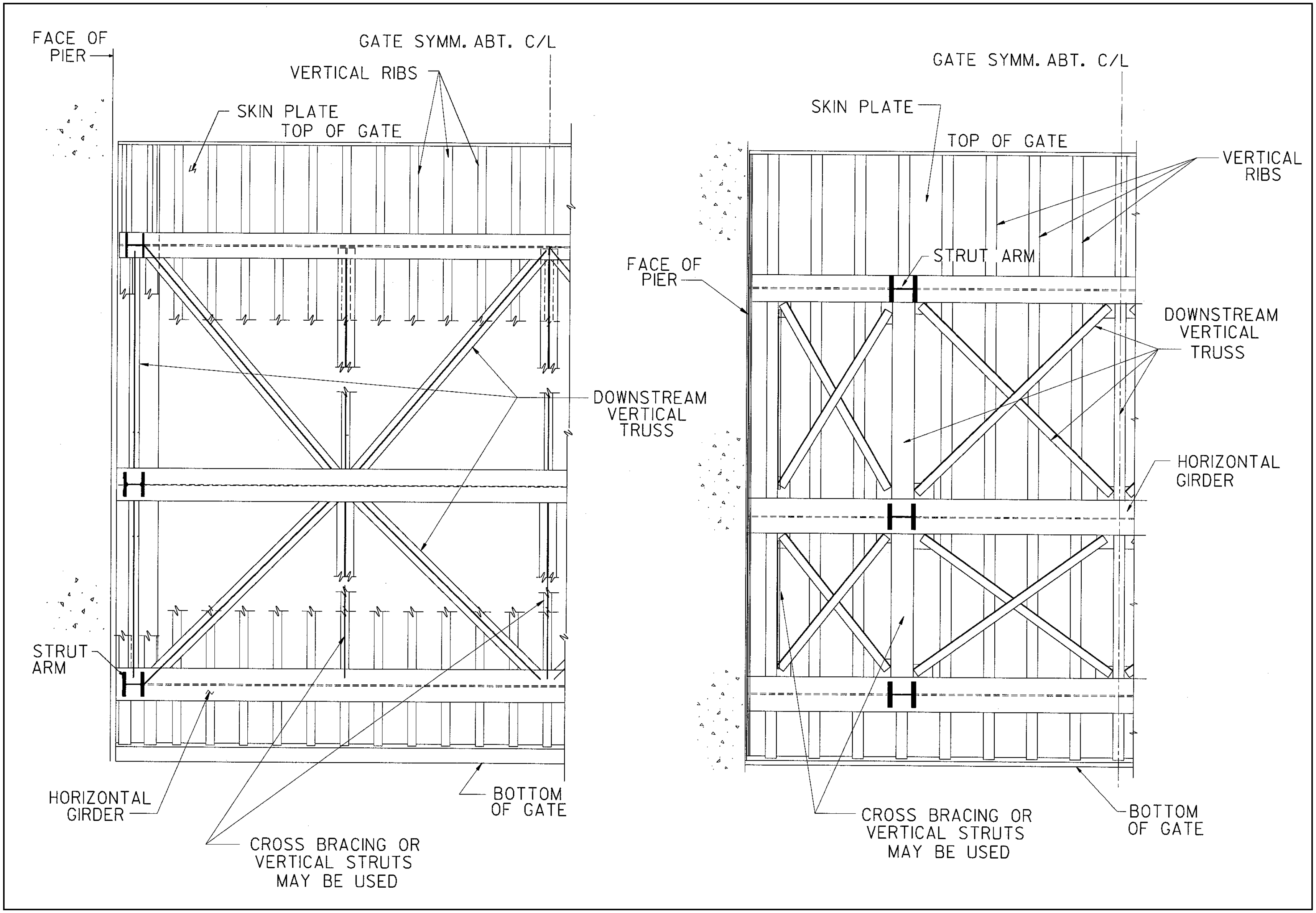


Figure 3-3. Downstream vertical truss (typical configurations)

bracing members located between one pair of adjacent horizontal girders are not in the same plane as those between the next pair. This out-of-plane geometry is commonly ignored for design purposes.

(c) End frame bracing. For the standard tainter gate configuration, bracing is provided for the end frame struts as shown by Figure 3-4. The end frame bracing members are ordinarily designed to brace the struts about the weak axis to achieve adequate slenderness ratios. As such, these members are considered secondary members. However, depending on their configuration and connection details, these bracing members may carry significant forces and act as primary members.

(d) Trunnion tie. A trunnion tie is a tension member provided on some gates with inclined strut arms that is designed to resist lateral end frame reaction loads (loads that are parallel to trunnion pin axis or perpendicular to the pier). Trunnion ties are not generally provided on gates with parallel strut arms, since the lateral reaction loads are normally negligible (paragraph 3-5.a(2)(c)). The trunnion tie extends across the gate bay from one end frame to the other and is attached to each end frame near the trunnion (Figure 3-5). The tie can be made up of a single member or multiple members depending on how it is attached to the end frames. Tubular members are often used.

(3) Gate lifting systems. Two standard lifting arrangements presently recommended for new construction are the wire rope hoist and hydraulic hoist system. The wire rope system incorporates wire ropes that wrap around the upstream side of the skin plate assembly and attach near the bottom of the skin plate as shown in Figure 3-6. The hydraulic hoist system incorporates hydraulic cylinders that attach to the downstream gate framing, usually the end frames (Figure 3-7). Hoist layout geometry is addressed in paragraph 3-2.c. Hoist loads and attachment details are addressed later in Chapter 3 and operating equipment is addressed in Chapter 7.

b. Alternative framing systems. In the past, many alternatives to the standard framing system have been designed and constructed. Each of these configurations may be suitable for certain applications and a brief description of some configurations is provided for information. The design guidance and criteria presented herein are not necessarily applicable to these gates.

(1) Vertical girders. For the standard gate configuration, fabrication at the trunnion and economy would normally limit the number of end frame strut arms to a maximum of four on each side. This in turn limits the design to four horizontal girders when each strut supports a horizontal girder. For tall gates, vertical girders have been used to simplify the end frame configuration. Curved vertical girders may be used to support several horizontal girders at each. Each vertical girder is supported by the corresponding end frame that may include two or more struts. The concept may be used with parallel or inclined end frames.

(2) Vertically framed gates. In vertically framed gates, vertical girders support ribs that are placed horizontally. With this configuration, horizontal girders and vertical ribs are eliminated. As with vertical girder gates, the vertical girders can be supported by two or more struts. This system has been used on small gates and gates with low hydrostatic head.

(3) Orthotropic gates. An alternative design approach is to design the gate as an orthotropic system. With the orthotropic approach, the skin plate, ribs, and horizontal girders are assumed to act as a stiffened shell. Typically, the ribs are framed into the horizontal girder webs. This approach can save material and gate weight, but fabrication and maintenance costs are often higher. Its use has been very limited.

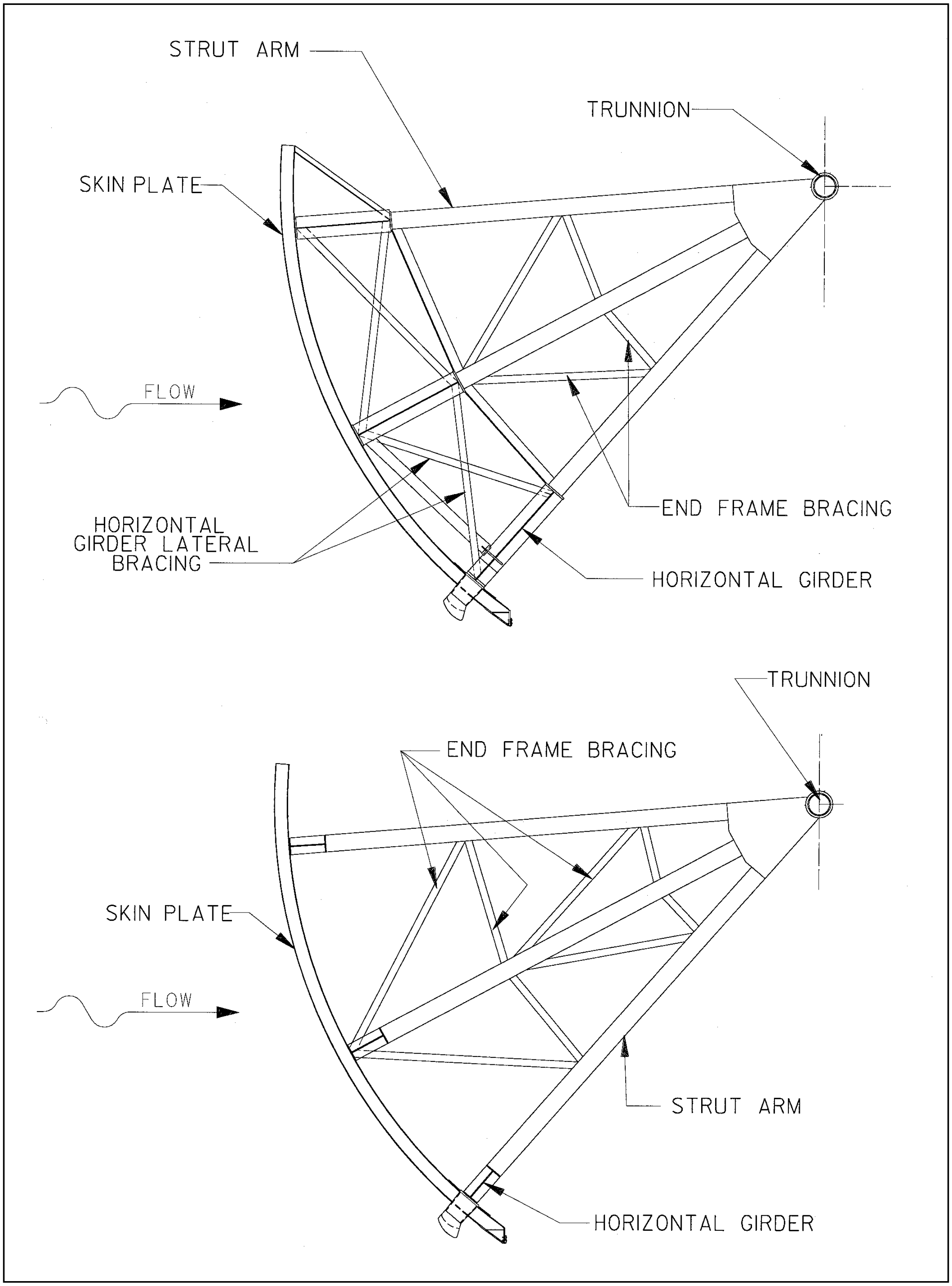


Figure 3-4. End frame bracing (typical arrangements)

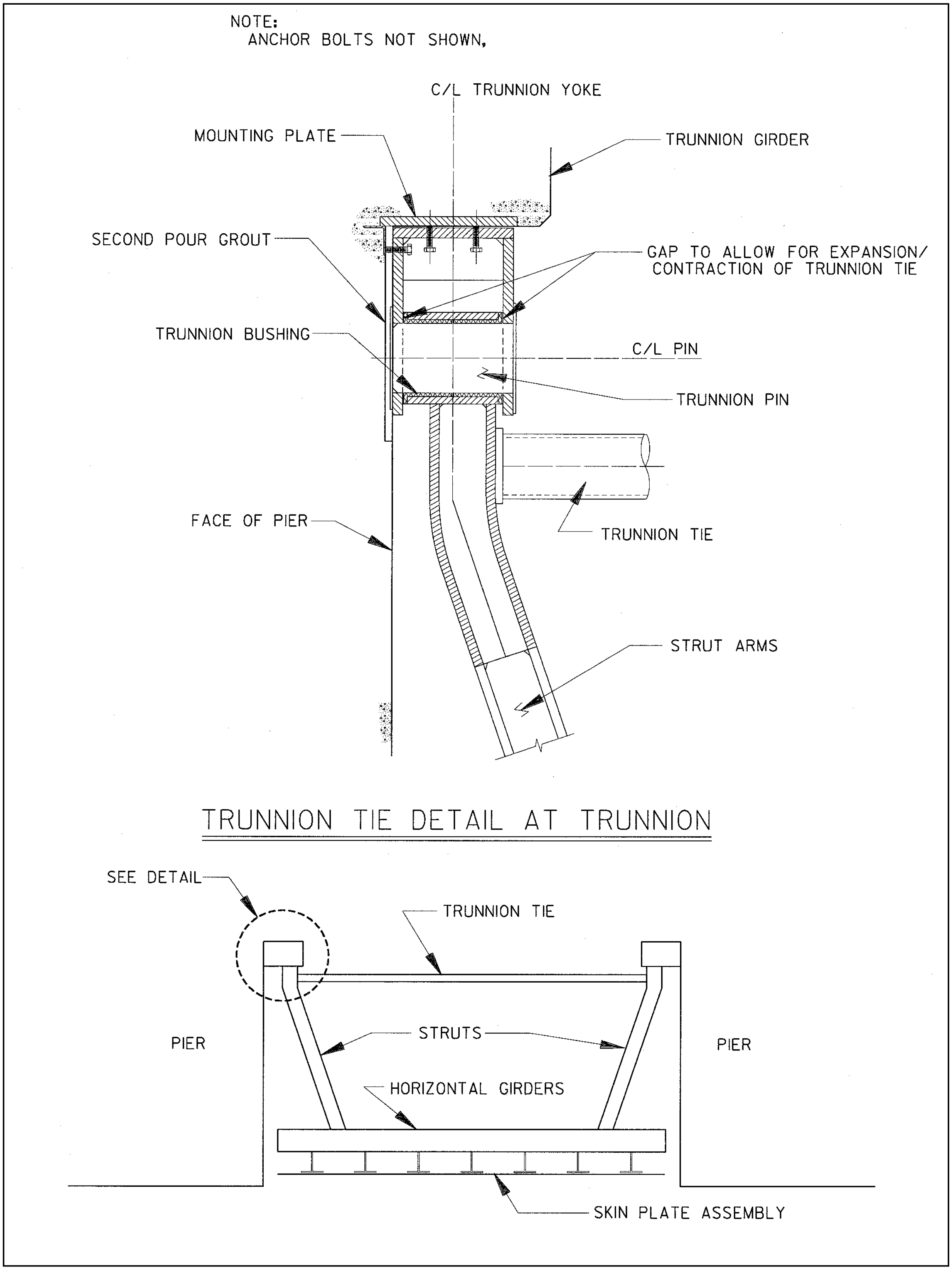


Figure 3-5. Trunnion tie

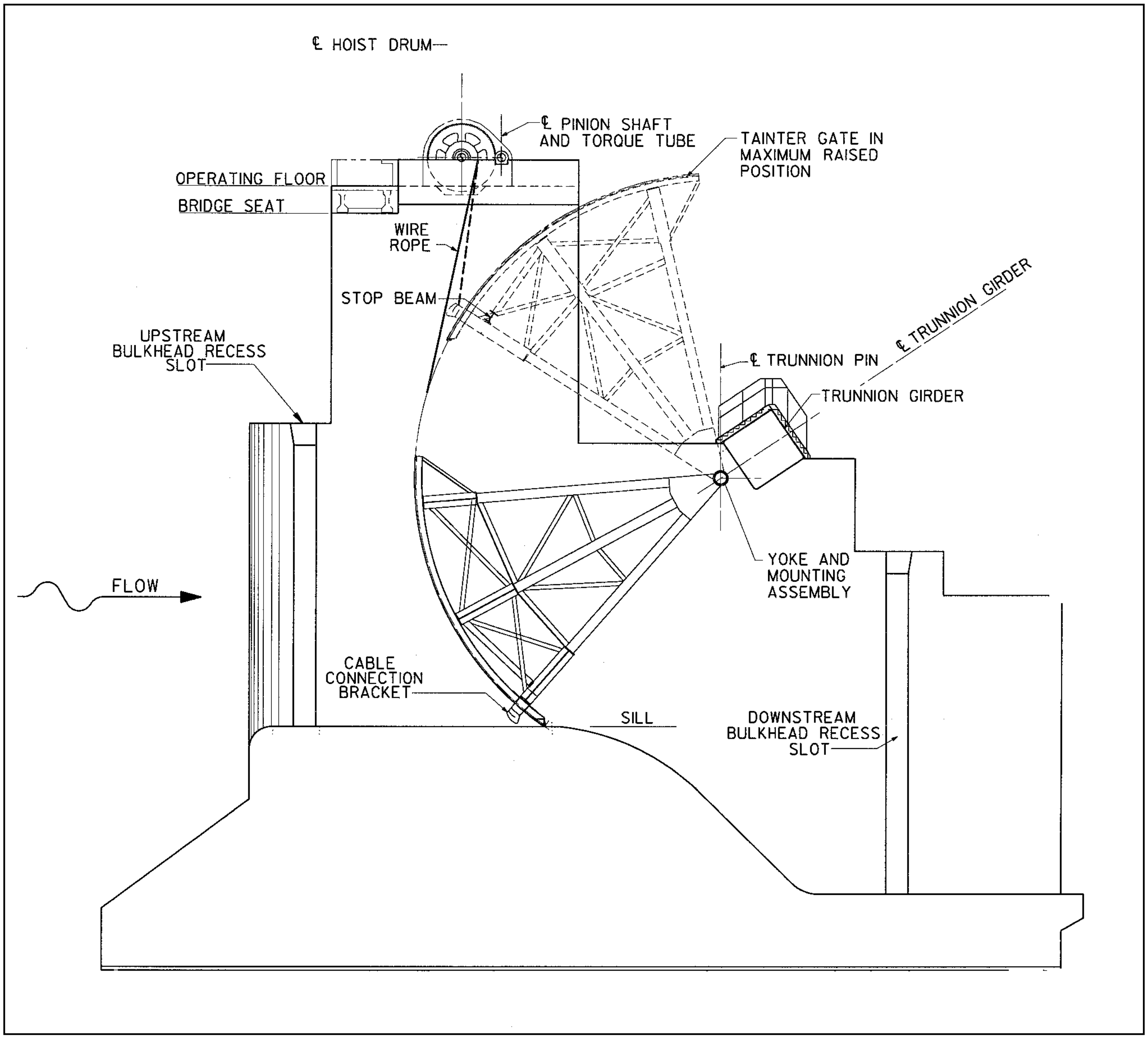


Figure 3-6. Example of wire rope hoist system

(4) Stressed skin gates. Stressed skin gates are a type of orthotropic gate in which the skin plate assembly is considered to be a shell or tubular structure spanning between trunnion arms. The skin plate is stiffened with horizontal and vertical diaphragms and intermediate stiffening members (usually horizontal tee sections parallel to the intermediate or midlevel horizontal diaphragm). As with other orthotropic gates, this type of gate can save material and gate weight, but fabrication and maintenance costs are often higher.

(5) Truss-type or space frame gates. Three-dimensional (3-D) truss or space frame gates were sometimes used in early tainter gate designs in the 1930s and 1940s. These early gates were designed as a series two-dimensional (2-D) trusses and were referred to as truss-type gates. They were typically as heavy or heavier than girder designs and fabrication and maintenance costs were very high. For this reason they were not adopted as a standard design. More recently, the use of computer designed 3-D space frame gates constructed with tubular sections has been investigated and may be practical in some situations.

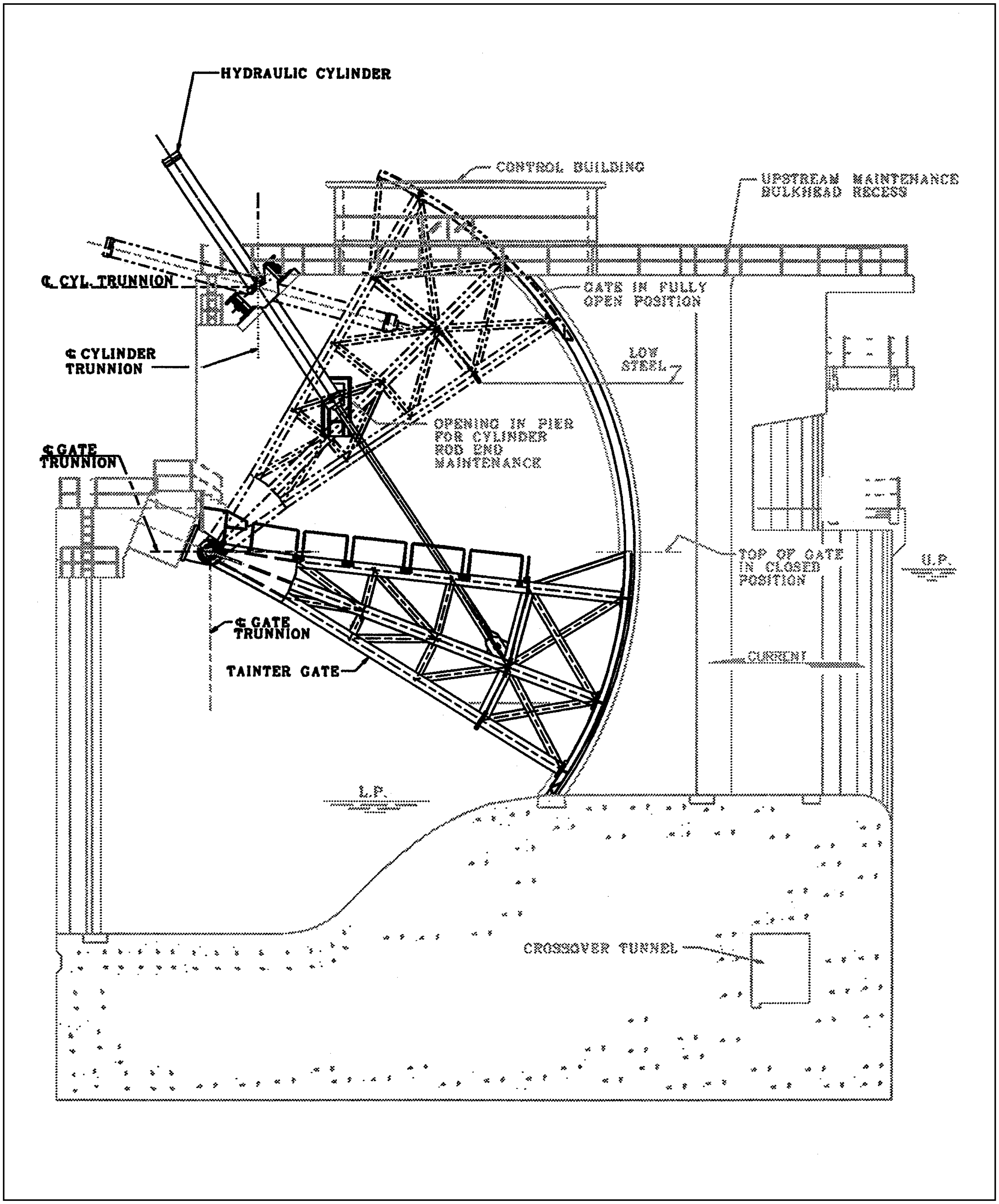


Figure 3-7. Hydraulically operated tainter gate

(6) Overflow/submersible gates. These gates may be of the standard configuration but are designed to allow water to pass over the top the gate. Deflector plates are often provided on the downstream side of the gate to allow water and debris to pass over the framing with minimized impact. Other gates have been designed to include a downstream skin plate, so the gate is completely enclosed. Vibration problems have been prevalent with this type gate.

c. General gate sizing and layout considerations. The sizing of the gates is an important early step in the design process. Gate size affects other project components, project cost, operation, and maintenance of the project. The following paragraph includes various considerations that should be taken into account while selecting a practical and economical tainter gate size. Related guidance can be found in EMs 1110-2-1603, 1110-2-1605, and 1110-2-2607. Appendix D provides pertinent data for a number of existing tainter gates. Each project is unique and the gate size and configuration should be determined based on careful study of the project as a whole. The best alternative is not necessarily a gate with the lightest gate weight-to-size ratio.

(1) Gate size. The hydraulic engineer will normally establish the limiting parameters for gate height and width. Within those limits, various height-to-width ratios should be studied to find the most suitable gate size for the project. The structural designer should coordinate closely with the hydraulic engineer in determining the basic limiting requirements for size and shape. The size, shape, and framing system of the gates should be selected to minimize the overall cost of the spillway, rather than the gate itself. Determination of gate size will also consider practical operation and maintenance considerations specific to the project.

(2) Gate width. The gate width will be determined based on such factors as maximum desirable width of monoliths, length of spillway, bridge spans, drift loading, overall monolith stability, and loads on trunnions and anchorages. On navigation projects, the gates may be set equal to the width of the lock, so that one set of bulkheads can serve both structures. It is usually desirable to use high gates rather than low gates for a given discharge, since the overall spillway width is reduced and results in a more economical spillway.

(3) Gate radius. The skin plate radius will normally be set equal to or greater than the height of the gate. The radius of the gate will also be affected by operational requirements concerning clearance between the bottom of the gate and the water surface profile. This is often the case for navigation dams on rivers where the gate must clear the flood stage water surface profile to pass accumulated drift. On such projects requiring larger vertical openings, it is common to use a larger radius, up to four times the gate height, to allow for a greater range of opening. This will require longer piers for satisfactory location of the trunnion girder.

(4) Trunnion location. It is generally desirable to locate the trunnion above the maximum flood water surface profile to avoid contact with floating ice and debris and to avoid submergence of the operating parts. However, it is sometimes practical to allow submergence for flood events, especially on navigation dams. Designs allowing submergence of 5 to 10 percent of the time are common. Gates incorporating a trunnion tie should not experience trunnion submergence. If other considerations do not control, it will usually be advantageous to locate the trunnion so that the maximum reaction is approximately horizontal to the trunnion girder (typically about one-third the height of the gate above the sill for hydrostatic loading). This will allow for simplified design and construction by allowing the trunnion posttensioned anchorage to be placed in horizontal layers.

(5) Operating equipment location. The type and position of the gate lifting equipment can have a significant effect on gate forces as the gate is moved through its range of motion. As stated previously, the two gate lifting systems recommended for new construction are the wire rope hoist system and the hydraulic hoist system.

(a) Wire rope hoist system. Generally, the most suitable layout for wire rope is one that minimizes the effects of lifting forces on the gate and lifting equipment. The three possible variations in cable layout include: 1) cable more than tangent to the skin plate, 2) cable tangent to the skin plate, and 3) cable less than tangent to the skin plate (Figure 3-8). Considering the gate and hoist system, the most ideal configuration is when the rope is pulled vertically and is tangent to the arc of the skin plate. For this condition, horizontal forces exerted to the hoist equipment are insignificant, and rope contact forces act radially on the gate. A nonvertical wire rope introduces a horizontal component of force that must be balanced by the operating equipment and associated connections. With a rope in the more-than-tangent condition, an edge reaction force exists at the top of the skin plate due to an abrupt change in rope curvature. This force affects the rope tension, trunnion reaction, and rib design forces. If the rope is in the less-than-tangent configuration, the rope force required to lift the gate increases exponentially as the direction of rope becomes further from tangent. The large lifting force affects the hoist and gate. Due to various constraints, some compromise on location of the hoist is usually required. Many gates have non-vertical wire ropes and many gates include ropes that are nontangent at or near the full, closed and/or full, opened positions.

(b) Hydraulic cylinder hoist system. Many new gate designs utilize hydraulic cylinder hoist systems because they are usually cost effective. However, these systems have some disadvantages and are not suited for all applications. Close coordination with the mechanical design engineer is required to optimize the hoist system. A hydraulic cylinder hoist system generally comprises two cylinders, one located at each side of the gate. Each cylinder pivots on a trunnion mounted on the adjacent pier, and the piston rod is attached to the gate. The cylinder magnitude of force and its orientation will change continually throughout the range of motion. In determining the optimum cylinder position, the location of the cylinder trunnion and piston rod connection to the gate are interdependent. Generally, the piston rod connection position is selected and then the cylinder trunnion position is determined to minimize effects of lifting forces. For preliminary design layouts, it is often assumed that the cylinder will be at a 45-deg angle from horizontal when the gate is closed, although optimization studies may result in a slightly different orientation. Generally, the most suitable location for the piston rod connection is on the gate end frame at or near the intersection of a bracing member and strut. It is preferable to have the piston rod connection above tailwater elevations that are consistent with the gate operating versus tailwater stage schedule; however, partial submergence may be acceptable for navigation projects. The connection location influences the gate trunnion reaction forces due to simple static equilibrium. When the connection is located upstream of the gate center of gravity, the dead load reaction at the gate trunnion will be downward while the gate is lifted off the sill. However, if the connection is downstream of the center of gravity, the reaction at the gate trunnion will act upward while the gate is lifted off the sill.

(6) Other sizing considerations. The face of gate and the stop log slots should be located far enough apart to permit the installation of maintenance scaffolding. Spillway bridge clearance is a factor in determining the gate radius and the trunnion location. Operating clearances from the bridge and the location of the hoist will usually require that the sill be placed somewhat downstream from the crest, but this distance should be as small as possible to economize on height of gate and size of pier. Additional considerations could include standardization of gate sizes on a project involving multiple spillways. The standardization of sizes could result in savings by eliminating multiple sets of bulkheads, standardizing machinery, and reducing stored replacement parts, etc.

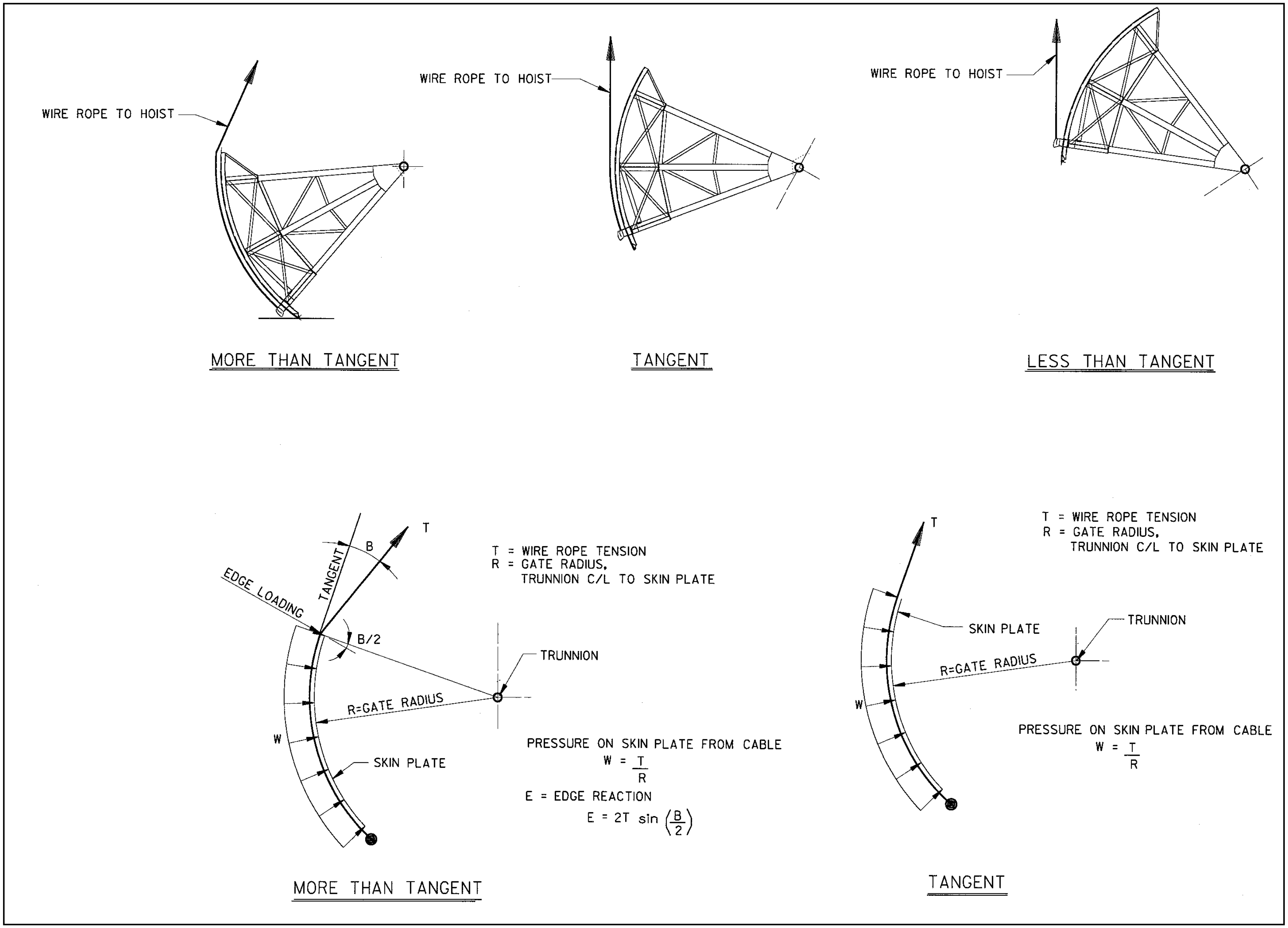


Figure 3-8. Loads due to various wire rope configurations

3-3. Material Selection

Structural members shall be structural steel. Embedded metals, including the side and bottom seal plates, should be corrosion-resistant stainless steel. Material selection for trunnion components is discussed in Chapter 4, and considerations for corrosion are discussed in Chapter 8. Table 3-1 provides a general reference for material selection of various tainter gate components, including American Society for Testing and Materials (ASTM) standards, given normal conditions. Material selection recommendations for various civil works structures including tainter gates is provided by Kumar and Odeh (1989).

Table 3-1
Tainter Gate Component Material Selection

Component	Material Selection
Skin plate, girders, trunnion girders, lifting bracket, wear plates, end frames	ASTM A36 or ASTM A572 Steel
Trunnion pin	ASTM A705, type 630 condition H 1150 steel forging[1,2] stainless steel[3] ASTM A27 or A148 cast steel
Trunnion bushing	ASTM B148 aluminum bronze ASTM B 22 manganese bronze or leaded tin bronze Self-lubricating bronze[4]
Trunnion hub	ASTM A27 cast steel ASTM A668 steel forging[2]
Trunnion yoke	ASTM A27 cast steel structural steel weldment
Seal plates and bolts	304 stainless steel
Lifting rope	308 stainless steel
J-seal keeper plate	410 stainless steel galvanized steel
Posttensioning anchorage steel	ASTM A772 Steel
Reinforcing steel	ASTM A615 grade 60 steel
Deflector plates	Ultra high molecular weight polyethylene

[1] Pin may be clad with corrosion resistant steel.
[2] If welded, carbon content not to exceed 0.35 percent.
[3] Type of stainless steel should be resistant to galling and crevice corrosion.
[4] Use with stainless steel pin.

3-4. Design Requirements

Tainter gate structural components shall be designed based on load and resistance factor design (LRFD) principles per EM 1110-2-2105. LRFD is a method of proportioning structures such that no applicable limit state is exceeded when the structure is subjected to all appropriate design load combinations. (See EM 1110-2-2105 and AISC (1994) for a more complete description of LRFD.)

a. Design basis. The basic safety check in LRFD may be expressed mathematically as

$$\Sigma \gamma_i Q_{ni} \leq \alpha \phi R_n \tag{3-1}$$

where

γ_i = load factors that account for variability in the corresponding loads

Q_{ni} = nominal load effects defined herein

α = reliability factor as defined in EM 1110-2-2105

ϕ = resistance factor that reflects the uncertainty in the resistance for the particular limit state and, in a relative sense, the consequence of attaining the limit state.

R_n = nominal resistance.

For the appropriate limit states (paragraph 3-4.c), all structural components shall be sized such that the design strength $\alpha\phi R_n$ is at least equal to the required strength $\Sigma\gamma_i Q_{ni}$. The design strength shall be determined as specified in paragraph 3-4.c. The required strength must be determined by structural analysis for the appropriate load combinations specified in paragraph 3-4.b.

b. Load requirements.

(1) Loads. Loads that are applicable to tainter gate design include gravity loads, hydrostatic loads, operating loads, ice and debris loads, and earthquake loads. Reactions are not listed below or in the load cases. Reactions loads are not factored since they are determined from equilibrium with factored loads applied. As a result, reaction forces reflect the load factors of the applied loads.

(a) Gravity loads. Gravity loads include dead load or weight of the gate (D), mud weight (M), and ice weight (C), and shall be determined based on site-specific conditions.

(b) Hydrostatic loads. Hydrostatic loads consist of hydrostatic pressure on the gate considering both upper and lower pools. Three levels of hydrostatic loads are considered. The maximum hydrostatic load H_1 is defined as the maximum net hydrostatic load that will ever occur. The design hydrostatic load H_2 is the maximum net hydrostatic load considering any flood up to a 10-year event. The normal hydrostatic load H_3 is the temporal average net load from upper and lower pools, i.e., the load that exists from pool levels that are exceeded up to 50 percent of the time during the year.

(c) Gate lifting system (operating machinery) loads. Operating machinery is provided to support gates during lifting or lowering operations. Under normal operating conditions, the machinery provides forces necessary to support the gate, and for the load cases described herein, these forces are treated as reaction forces. Loads Q are machinery loads for conditions where the machinery exerts applied forces on an otherwise supported gate (paragraph 3-4.b(2)(f)). There are three levels of loads applied by the operating machinery to the gate. The hydraulic cylinder maximum downward load Q_1 is the maximum compressive downward load that a hydraulic hoist system can exert if the gate gets jammed while closing or when the gate comes to rest on the sill. The hydraulic cylinder at-rest load Q_2 is the downward load that a hydraulic cylinder exerts while the gate is at rest on the sill (due to cylinder pressure and the weight of the piston and rod). Loads Q_1 and Q_2 do not exist for wire rope hoist systems. The maximum upward operating machinery load Q_3 is the maximum upward load that can be applied by the wire rope or hydraulic hoist systems when a gate is jammed or fully opened. The gate lifting systems exert forces on specific gate members whether the forces are reactions or applied loads. For example, where the wire rope bears on the skin plate, the rope exerts a contact pressure (line load) on the skin plate. The contact pressure force is equal to the rope tension force divided by the gate radius. If the wire rope is not tangent to the skin plate, the rope will exert an additional concentrated load on the gate (Figure 3-8.). Concentrated forces that typically vary with gate position in magnitude and direction are present at the attachment points for both gate lifting systems. Operating machinery loads must be quantified in consultation with the mechanical engineer that designs the machinery. Determination of load magnitudes and suggested coordination are discussed in Chapter 7.

(d) Ice-impact load *I*. The ice-impact load is specified to account for impact of debris (timber, ice, and other foreign objects) or lateral loading due to thermal expansion of ice sheets. Additionally, this load provides the overall structure with a margin of safety against collapse under barge impact. (Barge impact is an accidental event that is not practical to design for and is not specifically considered in design). *I* is specified as a uniform distributed load of 73.0 KN/M (5.0 kips/ft) that acts in the downstream direction and is applied along the width of the gate at the upper pool elevation.

(e) Side-seal friction load F_s. Loads exist along the radius of the skin plate because of friction between the side seals and the side-seal plate when the gate is opening or closing. The friction force per unit length along the skin plate edge dF_s/dl is equal to the product of the coefficient of friction and normal force between the seal plates and the side seals. For rubber seals, a coefficient of friction (μ_s) equal to 0.5 is recommended. (Seals that have Teflon rubbing surfaces provide a lower coefficient of friction and are recommended for serviceability. However, wear of the Teflon is a concern, and applying a lower coefficient of friction for design purposes is not recommended.) The normal force on the side seal is a function of the preset force in the seal and the hydrostatic pressure on the surface of the seal. For normal tainter gate configurations, side-seal friction can be approximated by Equation 3-2 (Figure 3-9).

$$F_s = \mu_s S\, l + \mu_s \gamma_w \frac{d}{2}\left(l_1 \frac{h}{2} + h\, l_2 \right) \tag{3-2}$$

where

μ_s = coefficient of side-seal friction

l = total length of the side seal

l_1 = length of the side seal from the headwater to the tailwater elevations or bottom of the seal if there is no tailwater on the gate

l_2 = length of the side seal from the tailwater elevation to the bottom of the seal (equals zero if there is no tailwater on the gate)

S = force per unit length induced by presetting the seal and can be approximated as

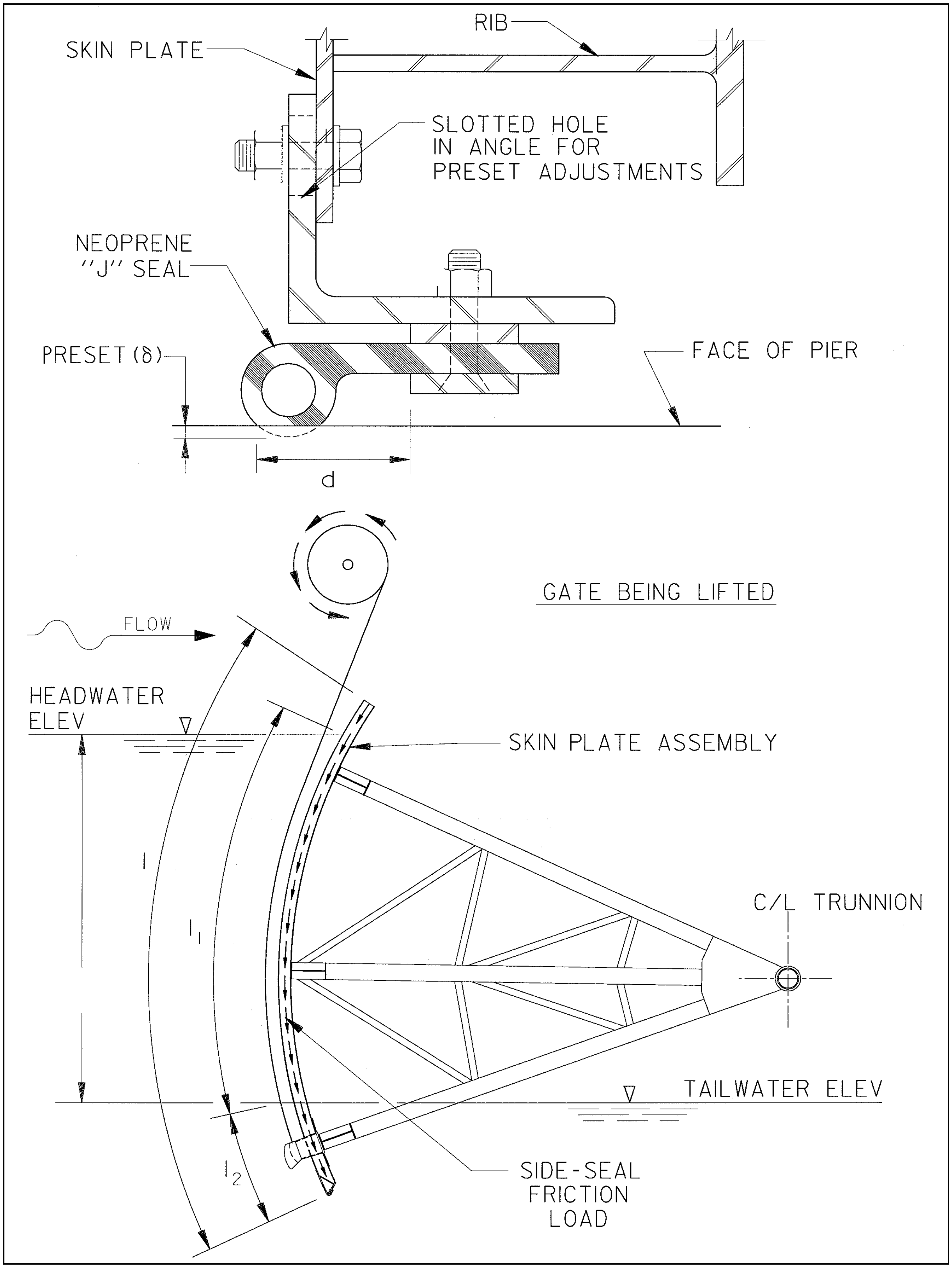


Figure 3-9. Standard side-seal arrangement and friction load

$S = \dfrac{3\delta EI}{d^3}$, where δ is the seal preset distance

γ_w = unit weight of water

d = width of the J seal exposed to upper pool hydrostatic pressure (Figure 3-9)

h = vertical distance taken from the headwater surface to the tail water surface or the bottom of the seal if there is no tailwater on the gate (Figure 3-9)

(f) Trunnion pin friction loads F_t. During opening or closing of gates, friction loads exist around the surface of the trunnion pin between the bushing and the pin and at the end of the hub between the hub bushing and side plate (yoke plate for yoke mounted pins) (Refer to Chapter 4 for description of trunnion components.). These friction loads result in a trunnion friction moment F_t about the pin that must be considered in design. The friction moment around the pin is a function of a coefficient of friction, the trunnion reaction force component R that acts normal to the surface of the pin (parallel to the pier face), and the radius of the pin. The friction moment at the end of the hub is a function of a coefficient of friction, the trunnion reaction force component R_z that acts normal to the end of the pin (normal to the pier face), and the average radius of the hub. The reaction forces R and R_z are discussed in paragraphs 3-5.a(2)(c) and 3-5.a(3). A coefficient of friction of 0.3 is an upper bound for design purposes. This is a conservative value that applies for any bushing material that may be slightly worn or improperly maintained. A realistic coefficient of friction for systems with lubricated bronze or aluminum bronze bushings is 0.1 to 0.15. The designer should ensure that detailed criteria are specified in project operations and maintenance manuals to ensure that trunnion systems are properly maintained.

(g) Earthquake design loads E. Earthquake design loads are specified based on an operational basis earthquake (OBE) with a 144-year mean recurrence interval. For gate design, the direction of earthquake acceleration is assumed to be parallel to the gate bay centerline (i.e., it is assumed that the effects of vertical acceleration and acceleration perpendicular to the gate bay are comparatively negligible). Earthquake forces include mass inertia forces and hydrodynamic forces of water on the structure. When a tainter gate is submerged, the inertial forces due to structural weight, ice, and mud are insignificant when compared with the hydrodynamic loads and can be ignored. For load case 1 (paragraph 3-4.b(2)(a)), the structure is submerged, and E shall be based on inertial hydrodynamic effects of water moving with the structure. For the structural member in question, E is determined based on the pressure that acts over the tributary area of the particular member. The hydrodynamic pressure may be estimated by Equation 3-3 (Westergaard 1931). This equation applies for water on the upstream and downstream sides of the structure.

$$p = \frac{7}{8}\gamma_w a_c \sqrt{Hy} \tag{3-3}$$

where

p = lateral hydrodynamic pressure at a distance y below the pool surface

γ_w = unit weight of water

H = reservoir pool depth (to bottom of dam) on upstream or downstream side of the structure

a_c = maximum base acceleration of the dam due to the OBE (expressed as a fraction of gravitational acceleration)

For load case 5 (paragraph 3-4.b(2)(e)), water is not on the structure, and E is due to mass inertia forces of the structure, ice, and mud.

$$E = a_c W_{D,C,M} \tag{3-4}$$

where

$W_{D,C,M}$ = weight of the portion of the structure, ice, and mud that are supported by the member in question.

(h) Wave load W_A. Wave loads are site specific and should be determined in consultation with the project hydraulic engineer. Guidance on development of wave loading is provided in the Shore Protection Manual (1984).

(i) Wind load W. Wind loads are site specific and should be calculated in accordance with ASCE (1995) but not more than 2.4 KPa (50 psf). Wind loads are small when compared to hydrostatic loads and only affect gate reactions when the gate is in an open position.

(2) Load cases. Tainter gates shall be designed considering the strength requirements for each of the following load cases and corresponding load combinations. The most unfavorable effect on various gate components may occur when one or more of the loads in a particular load combination is equal to zero. Various conditions are described for the cases of gate in the closed position (load case 1), gate operating (load case 2 and load case 3), gate jammed (load case 4), and gate fully opened (load case 5). The operating machinery may include forces in each load case; however, these forces are treated as gate reactions in some cases. As a result, the load Q does not appear in some load cases (paragraph 3-4.b(2)(f)).

(a) Load case 1: Gate closed. Load combinations for this load case (Equations 3-5, 3-6, and 3-7) apply when the gate is in the closed position.

$$1.4H_1 + 1.2D + 1.6(C+M) + 1.2Q_2 \tag{3-5}$$

$$1.4H_2 + 1.2D + 1.6(C+M) + [1.2Q_1 \text{ or } (1.2Q_2 + 1.2W_A) \text{ or } (1.2Q_2 + k_I I)] \tag{3-6}$$

$$1.2H_3 + 1.2D + 1.6(C+M) + 1.0E \tag{3-7}$$

1) Extreme pool condition. Equation 3-5 describes the condition where the maximum hydrostatic load H_1 is applied, gravity loads D, C, and M exist, and the hydraulic cylinders exert the at-rest load Q_2. (For gates with wire rope hoists, Q_2 does not exist.) It is assumed that the likelihood of the simultaneous occurrence of H_1 and W_A or I or E is negligible.

2) Operating pool condition. Equation 3-6 describes the condition for which the moderate hydrostatic load H_2 acts in combination with Q_1 or W_A or I. Gravity loads D, C, and M always exist, and it is assumed that Q_1, W_A, and I will not occur at the same time. The load Q_2 will likely always exist with W or

I. The I load factor k_I shall be equal to 1.6 when considering ice load due to thermal expansion and 1.0 when considering impact of debris.

3) Earthquake condition. Equation 3-7 describes the condition where the normal hydrostatic load H_3 acts in combination with earthquake loading E and gravity loads D, C, and M exist.

(b) Load case 2: Gate operating with two hoists. Load combinations for this load case (Equations 3-8 and 3-9) represent the condition when the gate is opening or closing with both hoists functional. Operating machinery loads Q are not listed in these load combinations, because it is assumed that the hoists are gate supports that will include reaction forces (paragraph 3-4.b(2)(f)). This load case does not include E because it is assumed that the likelihood of opening or closing the gate at the same time an earthquake occurs is negligible. Effects on members forces should be checked considering the entire operating range (any position between the sill and the upper gate stops) for gates either opening or closing.

$$1.4H_1 + 1.2D + 1.6(C+M) + 1.4F_S + 1.0F_t \tag{3-8}$$

$$1.4H_2 + 1.2D + 1.6(C+M) + 1.4F_S + 1.0F_t + (1.2W_A \text{ or } k_I I) \tag{3-9}$$

1) Extreme pool condition. Equation 3-8 (similar to Equation 3-5) describes the condition where the maximum hydrostatic load H_1 is applied, gravity loads D, C, and M exist, and friction loads F_s and F_t exist due to gate motion. It is assumed that the likelihood of the simultaneous occurrence of H_1 and W_A or I or E is negligible.

2) Operating pool condition. Equation 3-9 (similar to Equation 3-6) describes the condition for which the moderate hydrostatic load H_2 acts in combination with W_A or I. Gravity loads D, C, and M exist, and due to gate motion, friction loads F_s and F_t are applied. In the determination of H_2, the lower pool elevation will include a hydrodynamic reduction due to flow of water under the gate. The magnitude of hydrodynamic reduction should be determined in consultation with the project hydraulic engineer. As described for Equation 3-6, k_I shall be equal to 1.6 for ice and 1.0 for debris.

(c) Load case 3: Gate operating with one hoist. The load combination described by Equation 3-10 applies for the case where the gate is operated with only one hoist (subsequent to failure of the other hoist). Effects on members forces should be checked for all gate positions throughout the operating range for the gate either opening or closing.

$$1.4H_2 + 1.2D + 1.6(C+M) + 1.4F_S + 1.0F_t \tag{3-10}$$

For this case, the moderate hydrostatic load H_2 is applied, gravity loads D, C, and M exist, and friction loads F_s and F_t exist due to gate motion. In the determination of H_2, the lower pool elevation will include a hydrodynamic reduction due to flow of water under the gate (must be coordinated with the project hydraulic engineer). The effects of H_1, W_A, I, or E are not considered for this load case, since it is assumed that the likelihood of the simultaneous occurrence one of these loads and the failure of one hoist is negligible. Design considerations for this condition are provided in paragraph 3-5.e and serviceability considerations are discussed in paragraph 3-6.b(1).

(d) Load case 4: Gate jammed. The load combination of Equation 3-11 accounts for the possible condition where one hoist fails, and the gate becomes jammed between piers due to twist of the gate (such that one end frame is higher than the other). Effects on members forces should be checked with the gate jammed at positions throughout the operating range.

$$1.4\,H_2 + 1.2D + 1.6(C + M) + (1.2\,Q_3 \text{ or } 1.2\,Q_1) \tag{3-11}$$

For this case, the moderate hydrostatic load H_2 is applied in combination with the maximum machinery load Q_3 (for wire rope hoists or hydraulic hoists) or Q_1 (for hydraulic hoists), and gravity loads D, C, and M exist. It is assumed that only one hoist is functional. In the determination of H_2, the lower pool elevation will include a hydrodynamic reduction due to flow of water under the gate (must be coordinated with the project hydraulic engineer). The effects of H_1, W_A, I, or E are not considered for this load case, since it is assumed that the likelihood of the simultaneous occurrence one of these loads while the gate is jammed is negligible.

(e) Load case 5: Gate fully opened. The load combination of Equation 3-12 accounts for the condition where the gate is fully opened (raised to the gate stops) with wind, earthquake, or operating equipment loads.

$$k_D D + 1.6(C + M) + (1.3W \text{ or } 1.0E \text{ or } 1.2\,Q_3) \tag{3-12}$$

For this case, it is assumed that the gate is raised above the pool, so effects of H, W_A, and I are not included. Effects of Q_3 oppose gravity load effects, and effects of W or E may add to or oppose gravity load effects. When Q_3 is considered, or when effects W or E oppose those of gravity, C and M should be equal to 0 and the load factor k_D is equal to 0.9. When the direction of W or E is such that their effect increases gravity load effects, k_D is equal to 1.2 and C and M should be considered.

(f) Assumptions on support or loading of gate lifting systems (operating machinery). The load combinations included herein were developed for gate design based on various assumptions on loading and support conditions. (See Chapter 7 for discussion on criteria regarding load and operational requirements for operating machinery.) These assumptions must be considered in structural analysis of gate components (paragraph 3-5). For a tainter gate to be stable, rotational restraint must be provided by a suitable support. It is assumed that this support is the sill when the gate is closed (case 1), the hoists when the gate is operated (case 2 and case 3), the pier or some obstruction at the gate sides when the gate is jammed (case 4), and the hoists or the gate stops when the gate is fully opened (case 5). In load cases 2, 3, and some applications of 5, operating machinery loads Q are not included, since for these cases, the hoists are supports. The hoists provide reaction forces which are a function of all other gate loads. In load cases 1, 4, and some applications of 5, where the gate is supported by something other than the hoists, any force exerted by the hoists is an external load on the gate Q.

c. Limit states and design strength for individual members. EM 1110-2-2105 requires that strength and serviceability limit states be considered in the design of tainter gate structural components. Strength limit states include general yielding, instability, fatigue, and fracture. The design strength for each applicable limit state $\alpha\phi R_n$ is calculated as the nominal strength R_n, multiplied by a resistance factor ϕ and a reliability factor α. Except as modified herein, limit states, nominal strength R_n, and resistance factors ϕ shall be in accordance with AISC (1994). For normal conditions, α shall be equal to 0.9. For gates that are normally submerged and whose removal would disrupt the entire project, or for gates in brackish water or sea water, α shall be equal to 0.85. Fatigue and fracture design requirements are included in paragraph 3-8 and EM 1110-2-2105. Serviceability requirements for tainter gates are specified in paragraph 3-6. The following paragraphs provide specific guidance for the design of skin plate, ribs, girders, and end frame members.

(1) Skin plate. The skin plate shall be sized such that the maximum calculated stress is less than the yield limit state of $\alpha\phi_b F_y$. In determining the required strength, all load cases in paragraph 3-4.b shall be

considered; however, the ice-impact load *I* may be set equal to zero at the designer's option. This is frequently done, with the intent of allowing local damage to the skin plate for very infrequent loading events rather than increasing the gate weight.

(2) Rib members. Ribs shall be sized such that the maximum calculated moment M_u is less than the nominal bending strength of $\alpha\phi_b M_n$. In determining the required strength M_u, all load cases in paragraph 3-4.b shall be considered. For load cases 2, 3, and 4, the maximum effect will normally occur assuming that the gate is near the closed position.

(3) Girders. Girders shall be designed as beams or plate girders in accordance with AISC (1994). In determining the required strength, all load cases in paragraph 3-4.b shall be considered. For load cases 2, 3, and 4, the maximum effect will normally occur assuming that the gate is near the closed position.

(4) End frame. Struts and bracing members shall be designed as members under combined forces in accordance with AISC (1994). For gates not braced against side sway, struts shall be sized to avoid side sway frame buckling (lateral buckling of gate toward pier face, see paragraph 3-5.a(2)). In determining the required strength, all load cases in paragraph 3-4.b shall be considered.

(5) Secondary bracing members. The minimum axial design load in all bracing members shall be 2 percent of the total axial compression force or of the flexural compressive force in the compression flange of the corresponding braced member. Trunnion hub flange plates shall have adequate design strength to resist the required flexural and axial loads between the struts and the trunnion hub.

3-5. Analysis and Design Considerations

This paragraph includes guidance on design of tainter gate structural components (Chapters 4 through 6 provide guidance for the design of the trunnion and trunnion girder). The design and behavior of individual structural components are interrelated. The gate design should be optimized to achieve the most economical design overall, not necessarily to provide the most efficient geometry and member sections for each component. A large percentage of total gate cost is associated with the fabrication of the skin plate assembly. Therefore, the design process should be tailored to minimize the cost of the skin plate assembly considering the most normal load conditions. The required strength (design forces) and deflections for all structural components must be determined by structural analysis. Three-dimensional (3-D) analyses or more approximate (generally conservative) two-dimensional (2-D) analyses may be conducted. All analytical models must include boundary conditions that are consistent with load requirements specified in paragraph 3-4.b. Paragraph 3-5.a includes a description of acceptable 2-D models (various modeling alternatives exist), and the remainder of paragraph 3-5 provides general design considerations.

a. Two-dimensional analytical models. In the design of tainter gate structural members, it has been common practice to model the 3-D behavior with several independent 2-D models. With the 2-D approach, the overall behavior is simulated by modeling separately the behavior of the skin plate assembly (composed of the skin plate and supporting ribs), horizontal girder frames (composed of a horizontal girder and the two adjacent struts), vertical end frames (composed of struts and braces), and the vertical downstream truss. Analysis of the 2-D models is interdependent. Various loads on one model can be reactions from another (girder frame loads are obtained from the rib model reactions), and many of the same loads are applied to each model. Additionally, struts include member forces from separate models (the strong axis flexural behavior of the struts is simulated with the girder frame model, and axial and weak axis flexural forces are provided by the end frame model). An alternative for each 2-D model is described in the following subsections. In the discussion for each model, loads for all load conditions are described.

For design analysis, load combinations and associated load factors should be applied accordingly. Various loads that are applied to the models (such as the gate reaction loads including sill load R_S and the wire rope pressure load R_Q/r) are not factored, since they are a function of other factored loads.

(1) Skin plate assembly. For the 2-D approximate model, the skin plate and ribs are assumed to have zero curvature. The skin plate serves two functions. First, each unit width of skin plate is assumed to act as a continuous beam spanning the ribs in the horizontal direction (Figure 3-10). Second, the skin plate acts as the upstream flange of the ribs. The ribs, with the skin plate flange, are continuous vertical beams that are supported by the horizontal girders (Figure 3-11). A portion of the skin plate is considered to act as the upstream flange of the rib (paragraph 3-5.b(2)).

(a) Boundary conditions. Boundary conditions consist of simple supports located at each rib for the skin plate and at each girder for the rib members.

(b) Loads. Loading on the skin plate assembly consists of various combinations of factored loads and gate reaction loads. Factored loads consist of $1.2H$ or $1.4H$, $1.2\ W_A$, $1.0E$, $k_I I$, and $1.2Q_3/r$, and gate reaction loads include R_s and R_Q/r. H, W_A, E, I, and Q_3 are defined in paragraph 3-4.b, r is the gate radius, R_s is the sill reaction load at the bottom of the skin plate (load case 1 gate closed), and R_Q is the wire rope reaction load (for load cases 2 and 3 for gates with a wire rope hoist). The factored loads shall be applied in accordance with paragraph 3-4.b(2). Gate reaction loads R_S and R_Q/r are determined by equilibrium of the end frame model for each appropriate load condition (paragraph 3-5.a(3)) and are not factored since they are a function of other factored loads. For skin plate design, loads are determined based on a unit width of plate, and it is not considered necessary to include I and R_S. For the rib model, the magnitude for loads is determined based on the tributary area of the rib. For each rib, the tributary portion of R_S is resolved into a radial component that is applied as a concentrated load at the end of the rib cantilever, and a tangential component that is applied as an axial force. Although not applied directly, all loads described in paragraph 3-4.b can affect rib member forces, since the reaction forces at the sill or under the wire rope include the effects of trunnion friction F_t, hydraulic machinery loads Q_1 and Q_2, and gravity loads C, M, and D as defined in paragraph 3-4.b.

(c) Results. Analysis of the skin plate model will yield the calculated stresses and out-of-plane deflections necessary to size the skin plate in accordance with paragraphs 3-4.c(1) and 3-6. Analysis of the rib model yields the calculated moments necessary for rib design in accordance with paragraph 3-4.c and reactions are the girder loading for the girder frame model.

(2) Girder frame model. The 2-D analytical model is a single-story frame consisting of beam members that simulate the horizontal girder and two columns that represent the corresponding end frame struts (Figure 3-12). The strong axes of the struts are oriented to resist flexural forces in the plane of the frame. The model shown in Figure 3-12a applies for all load cases described in paragraph 3-4.b except the unsymmetric load cases 3 and 4. For these cases, the analytical model should include applied loads with an imposed lateral displacement to represent side sway of the frame (Figure 3-12b). For load case 3, the lateral displacement should be consistent with the expected displacement as determined by an appropriate analysis (paragraph 3-5.e). For load case 4, the maximum displacement (lateral displacement to the pier face) should be applied. For all load cases except load case 4, the frame is not braced against side sway and the analysis should be conducted accordingly (AISC (1994), Chapter C). For load case 4, the frame can be assumed to be braced with the maximum displacement applied.

(a) Boundary conditions. The supports for the structure are at the bottom of the columns or struts and should be modeled to simulate actual conditions. Where cylindrical pins are used at the trunnion, a fixed

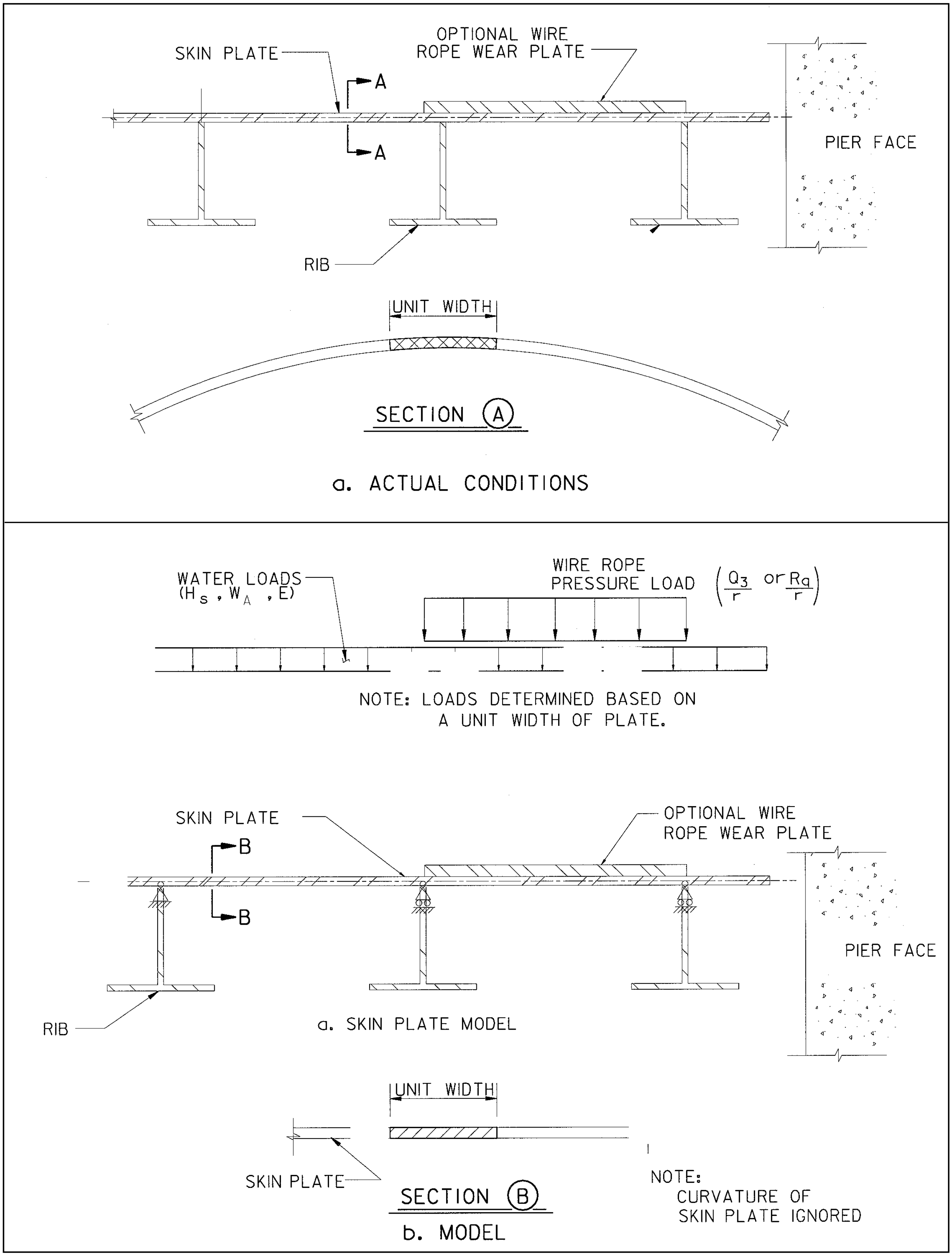


Figure 3-10. Skin plate 2-D design model

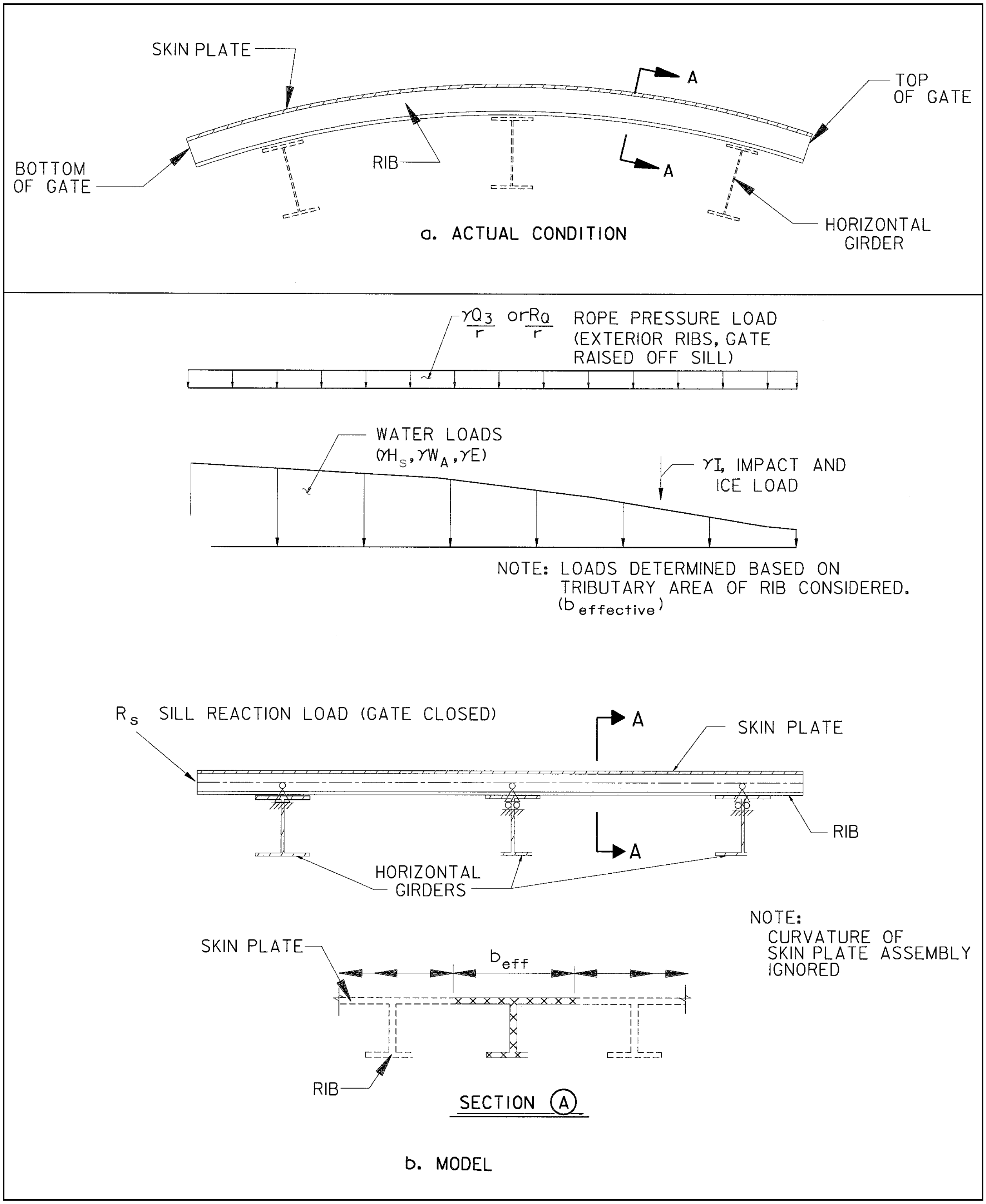


Figure 3-11. Skin plate assembly with ribs (2-D design model)

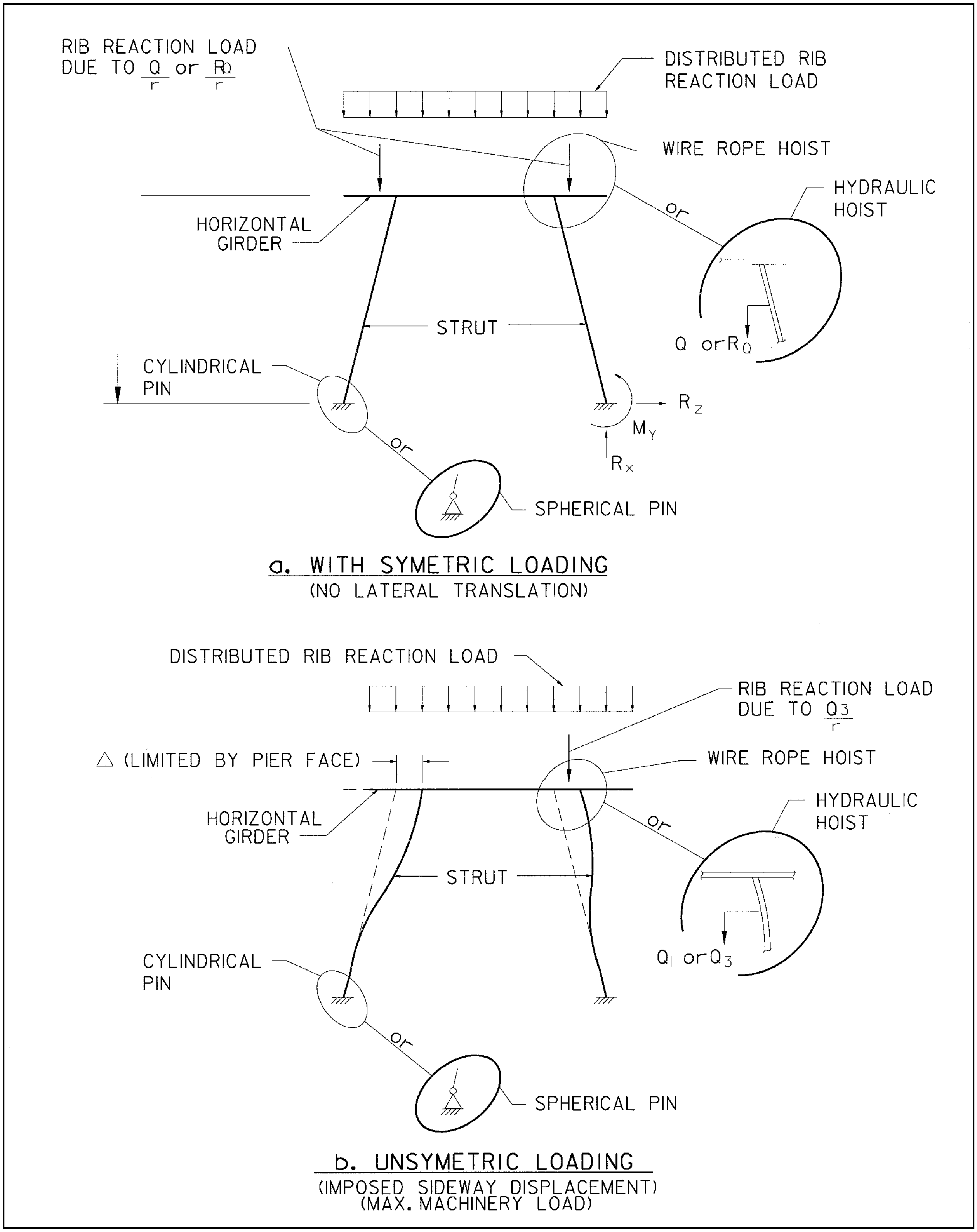


Figure 3-12. Girder model loads and boundary conditions

support should be assumed and where spherical bearings are used at the trunnion, a pinned support should be assumed.

(b) Loads. The girders support the skin plate assembly and loads to the girder are applied through the ribs. Therefore, for each load combination, girder loading is based on reaction forces from the rib model. A uniformly distributed load equivalent to the rib reactions distributed over each tributary area is applied along the length of the girder. This distributed load does not require a load factor, since the rib reactions are a function of factored loads. For gates with wire rope hoists, a concentrated load equal to the reaction for the rib that supports the wire rope should be applied to the girder at the corresponding rib location. The concentrated load is due to a distributed rib load equal to $1.2Q/r$ for load cases 4 and 5 or R_Q/r for load cases 2 and 3 (R_Q is determined by the end frame model described in paragraph 3-5.a(3)). For hydraulic hoists, the cylinder force load should be applied at the cylinder connection location (for most cases on the strut near the girder). This force is equal to $1.2Q$ for load cases 1, 4, and 5 or the cylinder force as determined by the end frame model analysis for load cases 2 and 3. All loads described in paragraph 3-4.b affect the girder frame member forces since components of each load are transferred through the ribs. It is assumed that girder lateral bracing resists girder torsional forces that are caused by gravity loads.

(c) Results. The girder frame analysis results include all design forces and deflections for the girder, flexural design forces about strong axis of the struts, and reactions that simulate lateral thrust R_z into the pier and moment at the trunnion M_y (Figure 3-12). The lateral thrust force R_z induces friction forces that are a component of trunnion friction moment F_t as discussed in paragraph 3-4.b(1)(f). The effect of R_z on F_T should be considered in the analysis of the end frame model. For gates with parallel end frames, the effect of R_z may be negligible. However, R_z is more significant for gates with inclined end frames, since R_z includes a component of the strut axial loads.

(3) End frame model. The analytical model for the end frame consists of elements to simulate struts and strut bracing, girders (webs), girder lateral bracing, and the skin plate assembly (Figure 3-13). Struts are modeled with frame elements, and bracing members are modeled with either frame or truss elements to be consistent with connection details. The elements that represent the skin plate assembly and girder webs are included in the model only to transfer loads and to maintain correct geometry. These elements should be relatively stiff compared to other elements. The girder members should be simulated by truss elements so the girder lateral bracing elements resist all forces transverse to the girder. (This will ensure that bracing is proportioned so that girder torsion is limited.) The assumed boundary conditions, loading, and model geometry are shown by Figure 3-13 for: a) gate closed (load case 1); b) gate operating with wire rope hoist (load cases 2 and 3); c) gate operating with hydraulic cylinder hoist (load cases 2 and 3); and d) gate jammed (load case 4) or raised to stops (load case 5). Boundary conditions and loading described in the following paragraphs are based on assumptions discussed in paragraph 3-4.b(2). The purpose of the end frame model is: a) to determine the sill reaction load R_S, operating machinery reaction load R_Q, and trunnion reaction R; and b) to determine end frame member design forces.

(a) Boundary conditions. For each model described by Figure 3-13, the trunnion is modeled as a pin free to rotate with no translation. For the gate-closed case, the boundary conditions for gates with wire rope or hydraulic hoists are identical as shown by Figure 3-13a. The gate is supported by the trunnion (modeled as a pin) and the sill. The sill boundary condition consists of a roller-pin free to translate tangent to the sill. For a 3-D model, the boundary condition along the sill should resist compression only (i.e., allow for deformation near the center of a gate that will likely result between the sill and gate bottom). There is no boundary condition for the hoist; a hoist force is treated as an external load. For gate-operating cases (Figures 3-13b and 3-13c), the gate is supported by the trunnion (modeled as a pin) and the hoist. (For this case, the hoist force is a reaction and not a load as discussed in paragraph 3-4.b(2)(f)). For wire

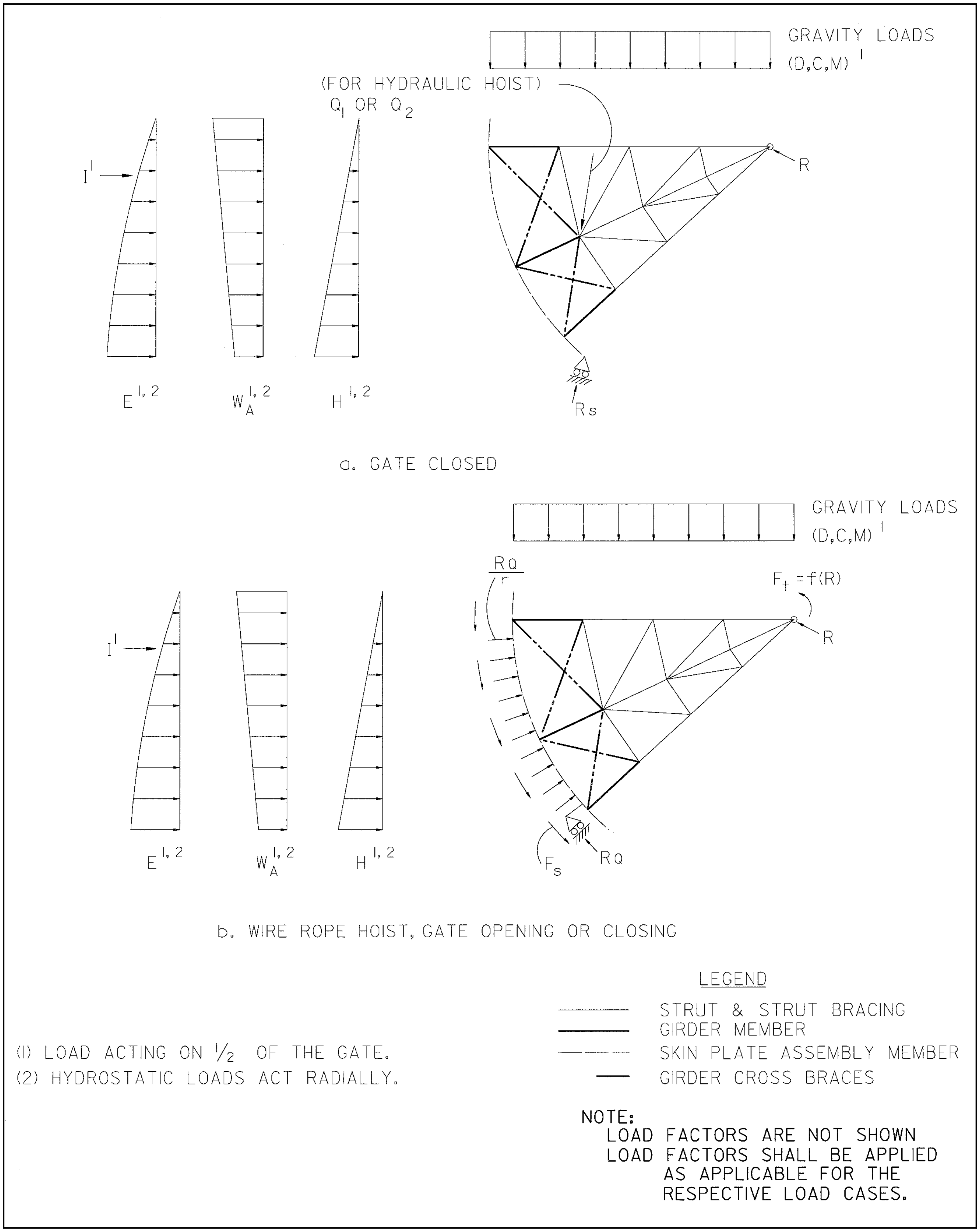
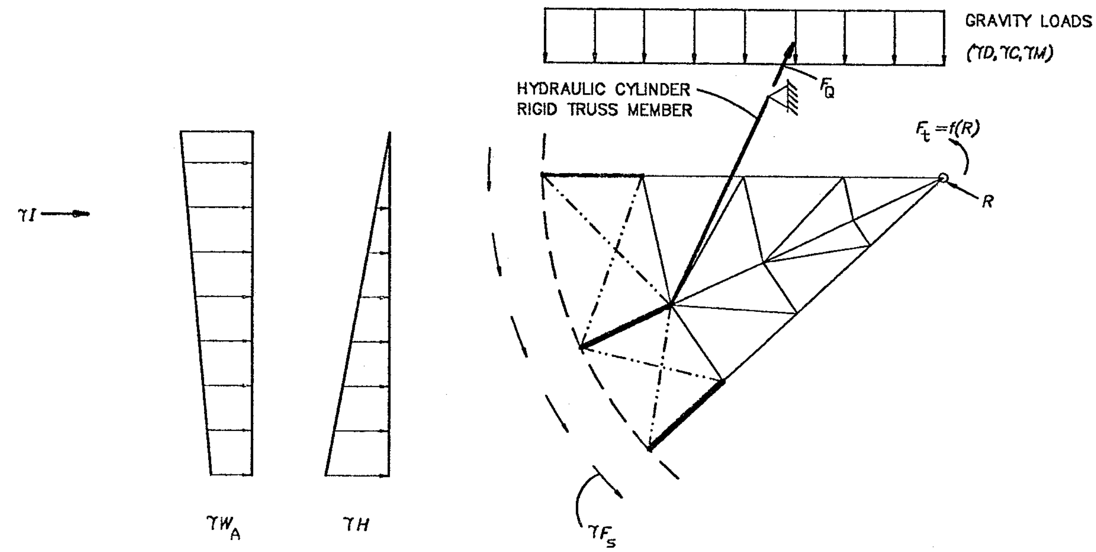
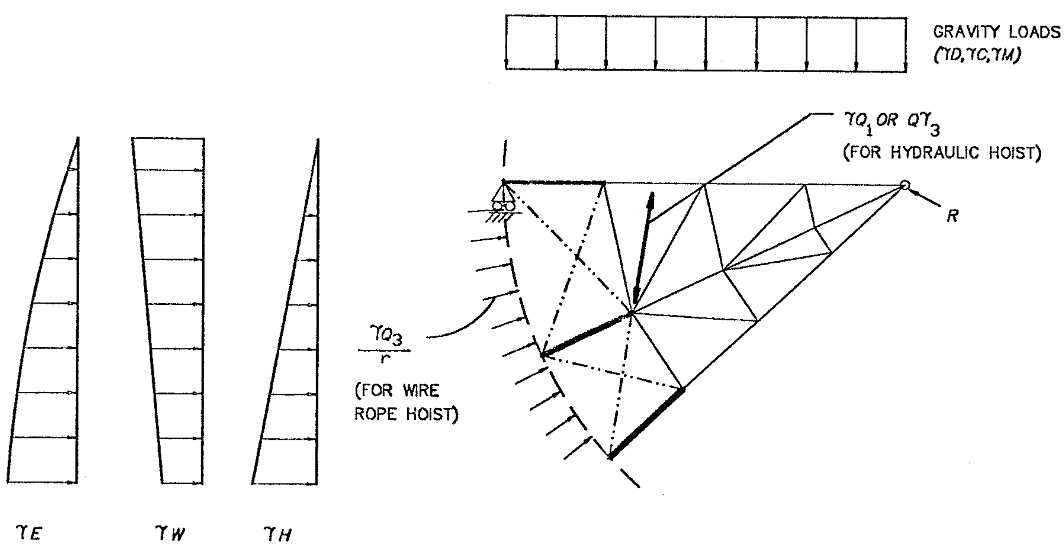


Figure 3-13. End frame 2-D model (Continued)



c. HYDRAULIC HOIST, GATE OPERATING (LOAD CASE 2 OR 3)



d. GATE JAMMED (LOAD CASE 4) OR FULLY OPEN (LOAD CASE 5)

NOTES:

(1) HYDROSTATIC LOADS ACT RADIALLY.

(2) GATE MAY BE ORIENTED ANYWHERE FROM CLOSED TO FULLY OPEN POSITION FOR THE GATE JAMMED OR GATE OPERATING CONDITION.

(3) FOR THE GATE OPERATING CASE, FRICTION LOADS F_t AND F_S ARE SHOWN FOR GATE OPENING. THESE LOADS ACT IN THE DIRECTION OPPOSITE TO THAT SHOWN FOR GATE CLOSING.

LEGEND

STRUT & STRUT BRACING
GIRDER MEMBER
SKIN PLATE ASSEMBLY MEMBER
GIRDER LATERAL BRACING

Figure 3-13. (Concluded)

rope hoists (Figure 3-13b), the boundary condition where the wire rope is attached to the skin plate assembly is modeled as a roller-pin support that is free to translate in the radial direction. For gates with a hydraulic hoist (Figure 3-13c), the cylinder is simulated by a rigid (very stiff) truss element positioned between the location of the cylinder connection to the end frame and the cylinder trunnion location. This is analogous to a roller-pin support located at the cylinder connection that is free to translate perpendicular to the hoist cylinder. (The cylinder connection to the end frame may include eccentricity out of the plane of the model depending on how the connection is detailed. If this is significant it should be accounted for in the design.) For the gate jammed or fully opened cases (Figure 3-13d), the gate is supported by the trunnion (modeled as a pin) and is restrained from rotation by the pier or some obstruction (gate jammed) or the gate stops (gate fully opened). The boundary condition to restrain rotation is a roller-pin support free to translate in the radial direction and located where the elements for the top girder and skin plate intersect or at another appropriate position along the skin plate.

(b) Loads. For each load case, the appropriate analytical model should include the combinations of factored loads as required by paragraph 3-4.b(2). With the gate closed, appropriate combinations of loads (1.2 or 1.4)H, 1.2D, 1.6(C + M), 1.2(Q_1 or Q_2), 1.2W_A, $k_I I$, and 1.0E are included as illustrated by Figure 3-13a. For wire rope systems, there is no force in the rope, so no operating machinery loads are included. For hydraulic hoist systems, the operating machinery force is treated as a load Q_1 or Q_2 since the machinery is not considered as a support. For load cases 2 and 3 (Figures 3-13b and 3-13c), loads include appropriate combinations of 1.4H, 1.2D, 1.6(C + M), 1.4F_s, 1.0F_t, 1.2W_A, and $k_I I$. Friction loads are present due to gate motion. The side-seal friction force F_s is applied along the perimeter of the skin plate, and trunnion friction moment F_t is applied at the pin support. Operating machinery loads Q (as defined in paragraph 3-4.b(1)) do not apply because the hoists serve as supports. However, for wire rope systems, the analysis must include the distributed load R_Q/r that acts radially wherever the rope contacts the skin plate. The wire rope tension is equal to the hoist reaction R_Q. Because external loads R_Q/r and the trunnion friction load F_t are a function of reaction forces R_Q and R (and the reactions are a function of external loads), a special analysis such as the iterative approach described in paragraph 3-5.a(3)(d) is necessary to determine the equilibrium state. As defined in paragraph 3-4.b(1)(f), the trunnion friction force F_t includes the effect of the end frame trunnion reaction R (parallel to the pier or abutment face) and the lateral strut reaction R_z (component perpendicular to the pier). R_z is estimated by analysis of the girder frame model. For load cases 4 and 5 (Figure 3-13d), loads include appropriate combinations of 1.4H, 1.2D, 1.6(C + M), 1.3W, 1.2Q_1 or 1.2Q_3, and 1.0E. For these cases, operating machinery loads Q are included since the hoists are not considered gate supports. For wire rope hoist systems, the analysis for load case 4 or load case 5 must include the factored distributed load 1.2Q_3/r which acts radially wherever the rope contacts the skin plate. For hydraulic hoist systems, the analysis should include the operating machinery load 1.2Q_1 or 1.2Q_3. (For load case 5, a downward load Q_1 may not be possible when the gate is fully opened, depending on gate arrangement.)

(c) Results. The end frame model provides strut weak axis flexural design forces, strut axial design forces, axial and flexural design forces for strut bracing, girder lateral bracing design forces, trunnion reaction forces, and operating equipment load requirements. The end frame model reaction forces R_s and R_Q are utilized in the other 2-D models as described in the previous sections.

(d) Iterative determination of reaction forces. For gate-operating cases in which external forces are a function of gate reactions, a special analysis such as iteration is necessary to determine forces and reactions because the reactions are a function of the external forces. Considering load case 2 or load case 3 with a wire rope hoist system, the trunnion friction moment F_t and distributed rope load R_Q/r (external loads) are a function of the trunnion reaction force R, and the hoist reaction force R_Q. A simple procedure to conduct the iteration is as follows:

1) Approximate the trunnion reaction R due to factored hydrostatic loading 1.4H and estimate the trunnion friction moment F_t as a function of R, R_z (determined from the girder frame analysis), the pin diameter, and coefficient of friction.

2) Determine the hoist reaction R_Q by equilibrium.

3) Recalculate the trunnion reaction R due to all appropriate factored loads (i.e., for load case 3, 1.4H, 1.2D, 1.6(C + M), 1.4F_s, 1.0F_t) including the reaction load R_Q/r.

4) Determine a modified trunnion friction moment F_t as a function of the modified reaction R, R_z (unchanged), pin diameter, and coefficient of friction.

5) Repeat steps 2 through 4 until the trunnion reaction R does not change significantly.

(4) Downstream vertical truss model. Bracing members that make up the downstream vertical truss are proportioned for forces that occur when the gate is supported at one end. To determine these forces accurately, a 3-D analysis is required because of the complex interaction of the skin plate assembly, end frames, and bracing members. However, various 2-D models can be used to conservatively approximate the forces. Figure 3-14 and the following paragraphs describe a recommended 2-D model. The simplified model shown in Figure 3-14b does not represent actual loading and support conditions but will provide approximate bracing forces for the simulated condition. Continuous frame elements simulate girder flanges, and the bracing members are represented by truss elements (include only axial forces). As stated in paragraph 3-2a(2)(b), out of plane geometry is ignored, and the truss members are assumed to lie in a single plane.

(a) Boundary conditions. With the analytical model described by Figure 3-14b, boundary conditions do not represent physical characteristics of the gate but provide geometric stability of the model. A roller-pin support free to translate in the horizontal direction is provided at the node where the shear load R_H is applied. This should be located at the end of the element that simulates the upper girder (near a bumper location or where the gate would contact the pier if rotation of the skin plate assembly were to occur). On the opposite corner of the model (opposite end of the lower girder), a pin support free to rotate with no translation is applied.

(b) Loads. Model loading (Figure 3-14b) consists of a horizontal shear load R_H. The magnitude of R_H as defined in Figure 3-14a is that required to maintain equilibrium with the gate subjected to vertical loads and suspended from one end. As described by the free body diagram of Figure 3-14a, the effects of factored loads 1.2D, 1.6(C+M), and 1.4F_s are included (simulates load case 3, paragraph 3-4.b(2)(c)). The trunnion friction load F_t and hydrostatic loads H, do not directly cause twisting of the gate and are not considered.

(c) Results. Truss members are to be sized to resist the calculated axial forces as determined by analysis of the downstream vertical truss model.

b. Skin plate assembly. The skin plate assembly consists of the skin plate and vertical ribs. Horizontal intercostals are not recommended since material savings realized in the design of the skin plate are offset by higher fabrication and maintenance costs. The designs of the skin plate and ribs are inter-related. The required skin plate thickness is dependent on the rib spacing (skin plate span), and the required rib size is dependent on the skin plate thickness since an effective portion of skin plate acts as a rib flange.

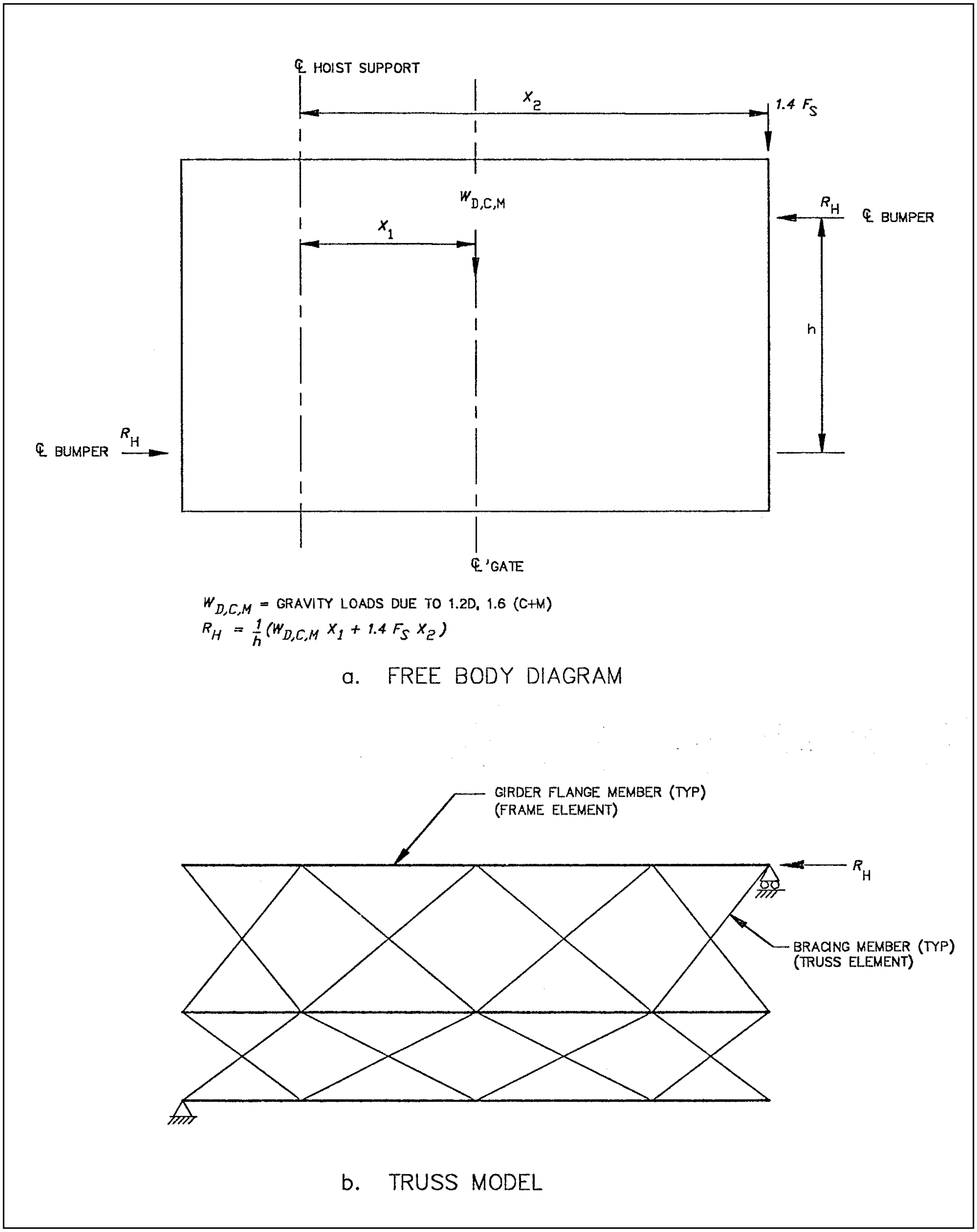


Figure 3-14. Downstream vertical truss model

(1) Skin plate design considerations. The skin plate design stress should be based on the negative moment at the supports for equally spaced interior ribs (fixed-end moment). The spacing between the exterior ribs at the ends of the gate should be adjusted such that the moment does not exceed the fixed-end moment of the interior spans. For gates with a wire rope hoist, thicker plate and/or closer rib spacing is normally required under the wire rope due to the rope pressure exerted on the plate. Because of the varying loading on the skin plate, it may be economical to vary the thickness of the plate over the height of the gate. For gates less than approximately 3m (10 ft) high, it is generally economical for the entire skin plate to be of one thickness. It is recommended to maintain a minimum thickness of 10 mm (3/8 in.), while a thickness greater than 20 mm (3/4 in.) will rarely be required for any gate.

(2) Rib design considerations. Although wide-flange or built-up sections are acceptable, structural tee sections with the web welded to the skin plate are recommended for ribs. In determining member geometric properties, an effective width of skin plate is assumed to act as the upstream flange of the vertical rib. The effective width b_e of skin plate shall be based on width-to-thickness ratios for compact or noncompact limits that are consistent with rib design assumptions. For rib sections that are considered as compact,

$$b_e = \frac{187t}{\sqrt{F_y}} \tag{3-13}$$

and for sections that are considered as noncompact,

$$b_e = \frac{255t}{\sqrt{F_y}} \tag{3-14}$$

where t is the skin plate thickness. Economical design for the ribs will be achieved by locating the horizontal girders (rib support locations) to minimize the bending moments, M_u with positive and negative moments approximately equal.

(3) Fabrication and maintenance considerations. General considerations are discussed in Appendix B.

(a) Skin plate. All skin plate splices shall be full penetration welds and smooth transitions shall be provided at splices between plates of different thickness. Corrosion is controlled by protective coating systems and maintenance, and increasing skin plate thickness to allow for corrosion is not recommended. (Chapter 8.) However, due to inevitable wear and deterioration, it is appropriate to increase the skin plate thickness along the bottom of the gate or under wire ropes for gates with wire rope hoists.

(b) Ribs. Ribs should be spaced and proportioned to provide adequate clearances required for welding and maintenance painting, even with a slight increase in steel quantity. The depth of the ribs must be sufficient to provide access for welding or bolting the rib flanges to the supporting girders. For welded construction, 200 mm (8 in.) has been considered a minimum rib depth in the past.

c. Horizontal girder. Girders provide support for the skin plate assembly and transfer all loads from the skin plate assembly to the end frames. The girders act as rib supports and are generally located to achieve an economical design for the ribs. However, the location of girders also affects the load on each girder since the rib reactions are the girder loads. The overall economy considering the effect on girder design should be considered. The end frame (strut) design affects girder forces since the struts are the girder supports.

(1) Design considerations. Horizontal girders are singly or doubly symmetric prismatic members that are designed primarily for flexure about their major axis. The distribution of flexure along the length of the girder is significantly influenced by the orientation of the end frames. Maximum girder moments will result with struts that are parallel to the pier face. The maximum girder moment is reduced (moments are redistributed) if the struts are inclined and will be minimized if the struts intersect the girder at approximately one-fifth the gate width from the pier face. With inclined struts, the limit state of lateral torsional buckling of the girder should be checked since a significant length of the downstream flange of the girder will be in compression. The unsupported length of the downstream flange is the distance between supports consisting of downstream vertical truss members and the end frame strut. (The upstream flange is laterally supported nearly continuously by the vertical ribs.) The downstream vertical truss is designed primarily to resist forces that occur when the gate is supported at only one end (paragraph 3-5.e.) and also provides lateral stability and resistance to torsional buckling for the girders. The tension flange of critical girders may be fracture critical and should be designed and fabricated accordingly (paragraph 3-8).

(2) Fabrication and maintenance considerations. Appendix B includes general guidance for inspection and welding. Girders may be rolled sections or built-up plate girders. The rib-to-girder connection, girder-to-strut connection, and bracing connections should be detailed to minimize concern for fracture (Appendix B). Drain holes with smooth edges should be provided in the girder webs at locations most appropriate for drainage. All stiffeners shall be coped. Use of a minimum number of girders will simplify fabrication and erection and facilitate maintenance. However, the overall economy considering the design of the skin plate assembly should not be compromised.

d. End frames. The end frames transfer loads from the girders and skin plate assembly to the trunnion. End frames include the struts and associated bracing and the trunnion hub flange plates. The arrangement and orientation of the end frames affects the magnitude and distribution of end frame and horizontal girder forces, trunnion fabrication, trunnion pin binding, and thrust forces into the pier. To achieve an economical design, these effects should be recognized considering all applicable load cases.

(1) Design considerations. Struts include flexure about both axes and significant axial forces. With a 3-D analysis, all forces are obtained from the same model. However, if a 2-D analysis as described in paragraph 3-5.a is utilized, the strut strong axis moments shall be determined from the girder model and the axial forces and weak axis moments shall be determined by the end frame model. End frame bracing should be spaced to achieve adequate weak axis slenderness ratios for the struts and must be designed to resist calculated forces. Bracing members may include significant flexural forces depending on member sizes, connection rigidity, and trunnion friction. Critical bracing members subject to flexural tension can be fracture critical and should be designed and fabricated accordingly (paragraph 3-8). Trunnion hub flanges shall be proportioned to resist the strut flexural, shear, and axial loads.

(2) Fabrication and maintenance considerations. Strut bracing members can be structural tee or wide flange sections; however, using wide flange sections with the same depth as the struts generally facilitates fabrication of connections. Trunnion hub flanges should be proportioned to provide a surface perpendicular to each strut with clearance provided between the ends of intersecting struts (Figure 3-15). Critical connections include the strut-to-girder connection (discussed in Appendix B) and the strut-to-trunnion hub flanges. The latter connection generally involves full-penetration butt splices involving thick plates, and welding requirements should be developed to minimize associated problems (Appendix B). The layout of end frames, parallel to the pier or inclined, is an important consideration regarding the overall design of the structure. Each configuration has unique advantages and disadvantages.

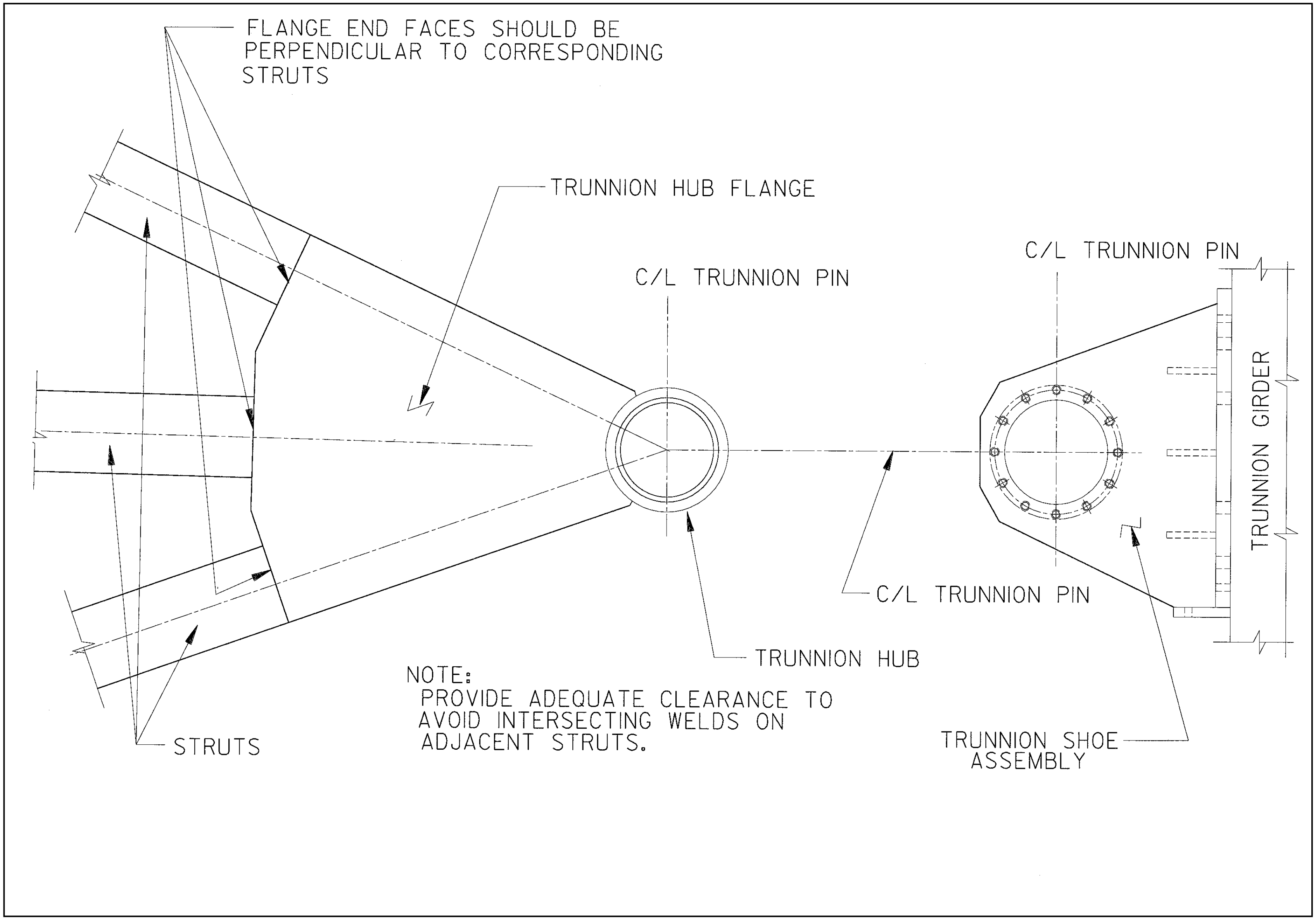


Figure 3-15. Trunnion hub flange

(a) Parallel end frames. End frames that are parallel to the pier and perpendicular to the horizontal girders are positioned such that interference to flow and debris accumulation on the struts is minimized. Fabrication and layout is relatively simple and struts that are parallel to the pier face transfer minimal lateral thrust into the piers. However, economy of the gate is sacrificed due to large flexural loads in the struts and girders, and clearance for maintenance painting between the pier and struts is limited.

(b) Inclined end frames. By inclining the end frames from the pier face, flexural forces are redistributed and the girder and strut flexural forces are reduced. The point of intersection of the strut and girder can be selected such that the girder moment at midspan is equal in magnitude to the cantilever moment as discussed in paragraph 3-5.c. With this arrangement, maximum economy of the girder design is achieved, and flexure in the end frames is minimal. A second option is to locate the intersection where there would be zero rotation in the horizontal girder. This would theoretically eliminate bending in the end frames. The side thrust component of the gate reaction introduced by inclining the end frames is transmitted directly to the pier or is resisted by a trunnion tie. Where the lateral thrust appreciably increases the pier requirements, it may be preferred to reduce the degree of inclination to achieve a more economical design. While inclined end frames are usually desirable for flood control projects, they are often not feasible for navigation dam projects where floating debris is a concern.

(c) Inclined frame layout. With inclined end frames, there are two options for layout of the struts. The struts can be positioned in a single vertical plane, or such that the girder end of each strut is an equal horizontal distance from the pier face. Placing struts in the same plane is generally recommended since fabrication is simplified and it will usually be cost effective.

1) Struts equal distance from pier. The struts can be positioned such that the connection between each strut and its corresponding horizontal girder is an equal horizontal distance from the pier face. In this case, the centerlines of the struts will form a conical surface with the apex at the trunnion. This results in complex fabrication of the strut-to-trunnion hub flange connection, since the struts are rotated with respect to one another and do not lie in one plane. However, this configuration has been widely used.

2) Struts positioned in a single plane. With struts positioned in a single vertical plane, only two struts can be at the same horizontal distance from the pier face. For gates with more than two girders, this results in differing support locations for the horizontal girders. However, fabrication of the strut-to-trunnion hub flange connection is simplified since all struts fall in a single plane. (This configuration is the only option for a vertical girder gate, since the struts and the vertical girder must fall in one plane.)

e. Downstream vertical truss. The primary structural purpose of the downstream vertical truss bracing members is to provide torsional rigidity for the condition when the gate is supported at one end. It also provides gate rigidity for resisting gravity loads with symmetric hoist support conditions, lateral bracing for the horizontal girders, and structural rigidity during field erection.

(1) Design considerations. For design purposes, bracing members should be sized to resist axial forces determined as described in paragraph 3-5.a(4). This procedure is conservative since the vertical support of the end frames and additional torsional rigidity of the skin plate assembly are ignored. Where practical, bracing should be placed in positions appropriate to provide lateral support to the girders. For gates that have a low height-to-width ratio, it may not be practical to design a bracing system that would prevent significant lateral displacements if the gate were supported on only one side. In these cases it may be necessary to provide side bumpers to limit lateral movement as described in paragraph 3-6.b(1).

(2) Fabrication and maintenance considerations. Single angles, double angles, or WT sections are commonly used for the bracing members. Connections between bracing members and the downstream girder flanges should be detailed to minimize fracture as discussed in paragraph 3-8 and Appendix B. The girder flange is subject to significant flexural tension and may be considered fracture critical in some cases. To limit accumulation of debris, deflector plates may be incorporated as described in paragraph C-2.b(4), Appendix C.

3-6. Serviceability

Tainter gates shall be designed considering the structure maintainability, durability, and operational reliability.

a. Corrosion. Gates shall be protected from corrosion by applying a protective coating system or using cathodic protection. Members shall be proportioned such that access is provided for future painting and maintenance. Chapter 8 provides guidance for corrosion protection, and paragraph 3-5 and Appendix B discuss fabrication considerations.

b. Operational reliability. Gates shall be designed such that they have a high degree of operational reliability in addition to adequate strength to resist applied loads.

(1) Sidesway and binding. Sidesway and binding shall be limited such that gate operation is not impeded. Gates may include various side bumpers or rollers (paragraph 3-7e) to limit or control side sway deflection and binding. For the condition where the gate is supported on only one side, the gate may rotate so that the gate bumpers bear on the side-seal plates. If this occurs, the normal force between the bumper and plate influences the potential for gate binding between piers due to frictional forces that occur with gate movement. A 3-D finite element analysis may be required to determine the normal forces and subsequent potential for binding. Such an analysis would be nonlinear, since the boundary condition would vary depending on whether or not the bumper touches the side-seal plate. Gap and hook support elements, which allow a specified movement to occur before developing a reaction force, may be appropriate for modeling such support conditions. If operational requirements include lifting or closing the gate when it is supported on one side only, the designer should consider possibilities of roller failure or degraded embedded metal surface conditions (due to corrosion or presence of foreign materials/growths) on the effective roller drag or frictional resistance.

(2) Ice control. Where ice may accumulate and inhibit gate operation, heaters shall be considered in the design. Various gate heaters are discussed in Appendix C.

(3) Deflections. Deflections under service loads shall not impair the serviceability or operability of the gate. Girder deflections shall be limited to avoid unwanted vibrations and leakage at the sill, and plates must be sized to avoid plate membrane behavior. The maximum girder deflection between end frames shall be limited to 1/800 times the span, and the maximum girder deflection for the cantilever portion between the end frame and pier face shall be limited to 1/300 times the cantilever length. The skin plate deflection shall be limited to 0.4 times the plate thickness.

(4) Vibration. Vibration due to flow under the gate shall be considered in the design and detailing of the tainter gate. Deflections shall be limited in accordance with paragraph 3-6.b(3). To limit vibration, the bottom lip of the tainter gate and sill should be detailed as described in paragraph 3-7.a(2) (Appendix C, paragraph C-2.b(1)).

(5) Debris. Consideration should be given to debris buildup in cases where there will be downstream submergence. Debris protection should be provided as needed on the end frames and on the downstream flanges of girders to avoid debris impact damage and binding of lodged debris (paragraph C-2.b(4)). In extreme cases, floating debris swirling behind the gate has damaged lighter members such as bracing members. To avoid damage, some gates have been fitted with downstream deflector plates to protect the framing from impact due to debris.

3-7. Design Details

a. Seals. The seals used in tainter gates follow standard details. However, there will be some differences based on operational requirements and the degree of water tightness required for the specific project.

(1) Side seals. The standard side-seal arrangement is shown in Figure 3-9. This arrangement employs standard, readily available, J-bulb seals. The seals may have a hollow bulb where increased flexibility of the bulb is desired such as low head applications. The seals are available with the rubbing surface coated with fluorocarbon (Teflon) to reduce friction. This is beneficial especially for high head gates. The seal attachment plate must have slotted bolt holes to allow for field adjustment of the seals. The seals are normally installed with a precompression against the side-seal plate which allows for construction irregularities and creates a tighter seal under low heads. The standard side-seal configuration provides for an increase in the sealing force in proportion to increased head and seals usually tend to leak under low heads rather than high heads.

(2) Bottom seals. The recommended bottom-seal configurations are shown in Figure 3-16. For most conditions, the preferred configuration is that shown by Figure 3-16a. The seal is provided by direct contact between the skin plate edge and the sill plate. The lip of the tainter gate should form a sharp edge and the downstream side of the lip should be perpendicular to the sill. It is recommended that rubber seals not be used on the gate bottom unless normal leakage can not be tolerated. If leakage is critical, a narrow rubber bar seal attached rigidly to the back side of the gate lip should be used (Figure 3-16b). An alternative to this is the configuration shown by Figure 3-16c with a rubber seal embedded in the gate sill plate.

b. Lifting attachments. Lifting attachments are often generally treated as fracture critical, non-redundant connections for design. However, redundancy actually does exist since there are two lifting attachments. The force in the attachment due to the machinery's operating at maximum stall pull (Load Case 4) normally governs the design rather than normal operating forces. The magnitude of this loading will be obtained from the mechanical engineer responsible for the machinery design and will be based on the capabilities of the lifting equipment. The wire rope attachment often must be designed with a rotating attachment to allow the cable to pull away from the skin plate as the gate approaches the full open position. Many gates also have skin plate extensions of smaller radius at the top to allow the rope to wrap over the top of the gate when fully closed. A typical wire rope attachment detail is shown in Figure 3-17. A typical hydraulic cylinder attachment detail is shown in Figure 3-18.

c. Drain holes. The designer should consider all locations where water can be trapped for all gate positions. Long-term standing water should be avoided, since it contributes to corrosion and becomes stagnant ponds of scum. Drain holes properly located for drainage should always be provided in the webs of the girders, end frames, and bracing members where applicable. The typical size is 5 cm (2 in.) in diameter. Additionally, half round holes can be provided in stiffener plates along with extra large corner copes to avoid pockets of water between stiffeners. Holes in flanges should generally be avoided.

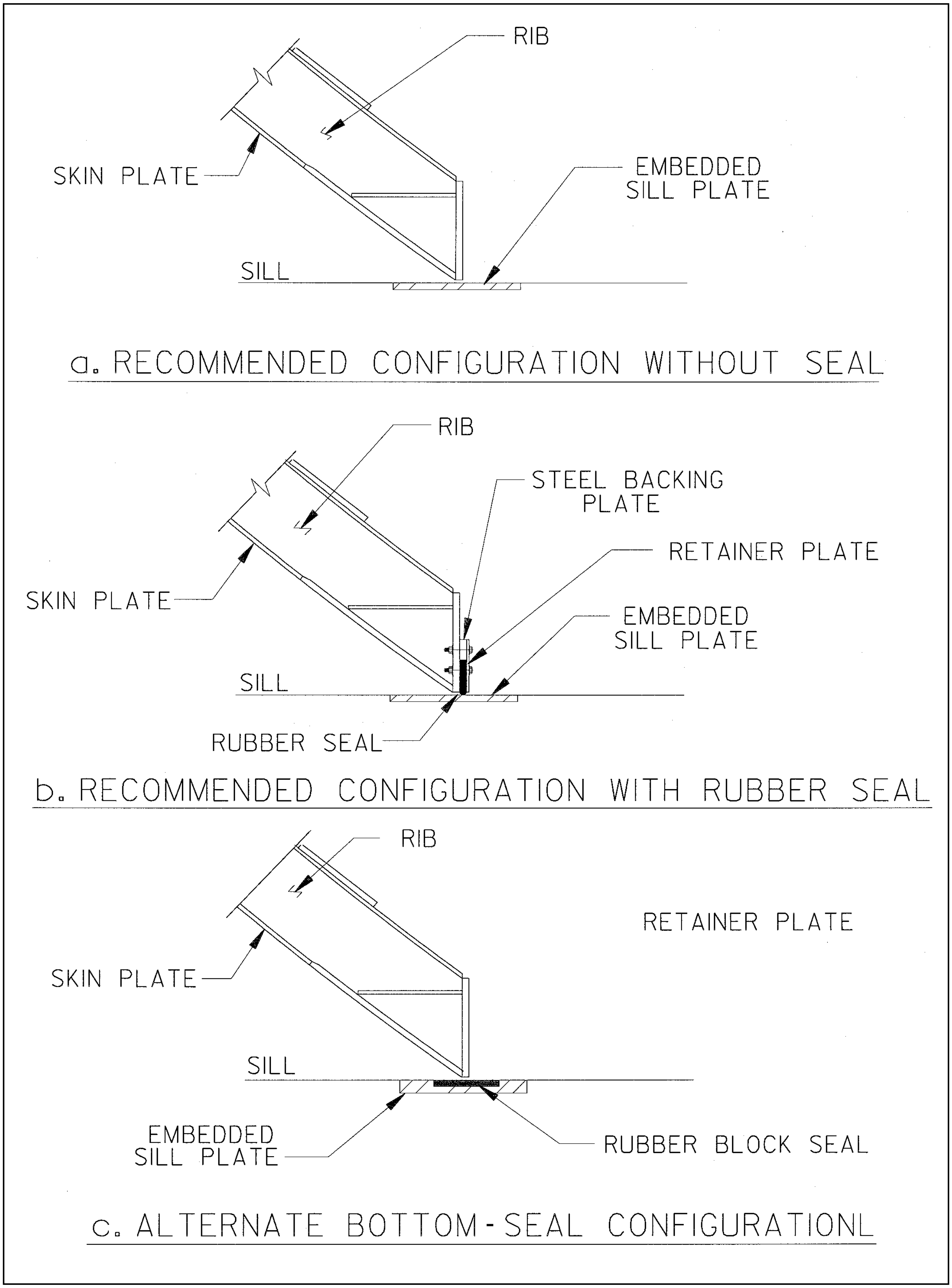


Figure 3-16. Bottom-seal configurations

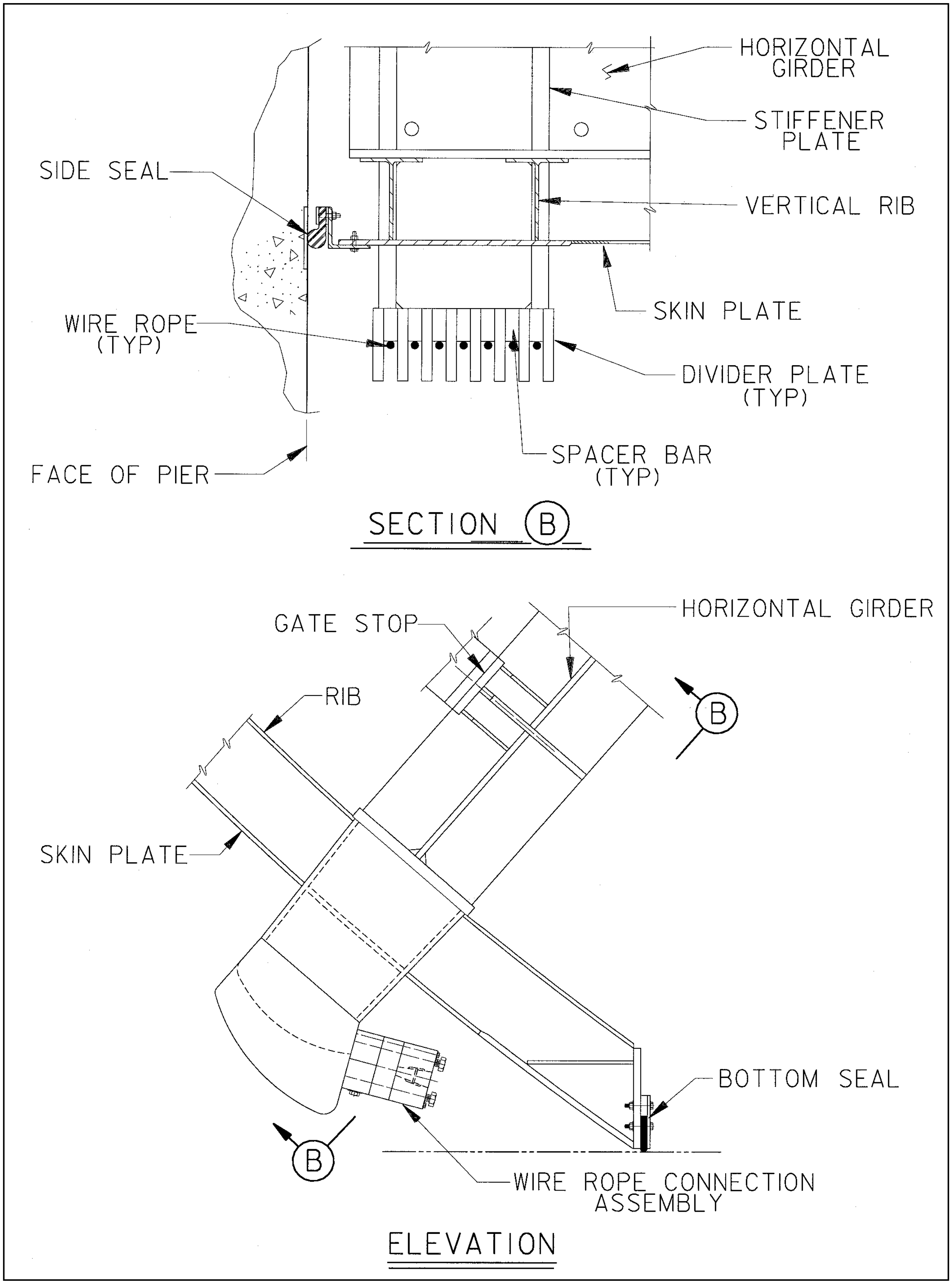


Figure 3-17. Wire rope connection bracket

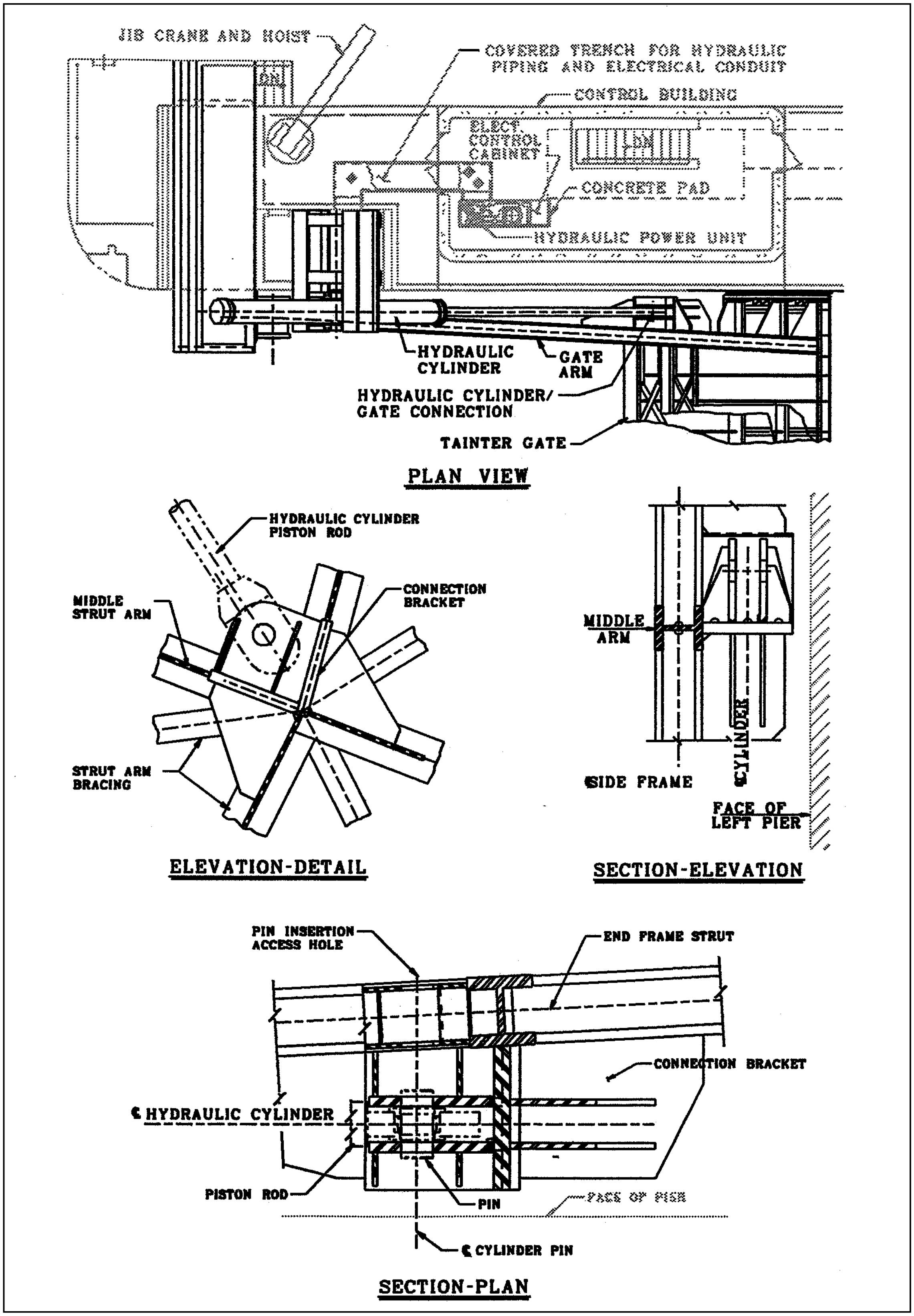


Figure 3-18. Hydraulic cylinder gate connection

d. Gate stops. Many structures are provided with gate stops which limit the gate from traveling beyond some point of opening. The stops are usually a short section of steel beam embedded and anchored into the pier which will contact a bumper on the gate if the gate travels beyond a certain position (Figure 3-19). The gate stops are not provided to physically stop the gate from opening since the machinery will be designed to stop prior to the gate contacting the gate stops. The stops are provided to keep the gate from over traveling due to wind or water loading in extreme or unusual situations. The stops are more often used with the wire rope hoist system since the ropes offer no resistance to upward movement.

e. Bumpers. Bumpers or rollers are generally located at the ends of the top and bottom horizontal girders near the upstream or downstream flanges. Bumpers are usually fitted with a bronze rubbing surface. An alternative for a bumper detail is shown in Figure 3-20. Rollers or ultra-high molecular weight plastic rubbing surfaces may be used to reduce friction when binding may impact gate operation.

f. Dogging devices. Some gates are provided with devices to temporarily support the gate in a full or partially raised position. These dogging devices will relieve the load on operating machinery and can even allow for maintenance or repair of the machinery or gate while the gate is raised.

3-8. Fracture Control

Design shall include provisions for fracture control of fracture critical members (FCM) and other critical elements that include tensile stress. Fracture control includes detailing tension connections to minimize stress concentration, specification of material properties, and enforcing prudent fabrication and inspection procedures. Guidance on preparation of project specifications is provided in Appendix B and ER 1110-2-8157. General requirements for welded connections are included in EM 1110-2-2105.

a. Fracture critical members. Fracture critical members or member components are tension members or tension components of flexural members , the failure of which would result in collapse of the structure. The design engineer shall identify all FCM on the project plans, and appropriate provisions on materials and fabrication requirements shall be included in the project specifications. These provisions shall conform to requirements specified in EM 1110-2-2105. Fracture critical members may include lifting machinery components and associated connections, tension flange of critical girders, tension flange of steel trunnion girders, and tension members of end frames.

b. Critical tension elements. Special considerations are warranted for various members or elements that are critical to structural or operational function but are not fracture critical. The engineer shall determine critical elements susceptible to fracture (i.e., strut-arm-to-girder connection) and specify any nondestructive examination requirements (other than visual inspection) of welds. Nondestructive examination is discussed in Appendix C.

c. Thick plate weldments. Appropriate fabrication requirements including weld sequence and inspection requirements shall be specified for thick plate weldments or highly constrained weldments that will include large tensile residual stresses (Appendix B). Trunnion yoke plates, trunnion bushing assembly, cable attachment brackets, steel trunnion girders, and built-up members generally include weldments with thick plates and/or high constraint. (A thick plate is generally considered to be 38 mm (1-1/2 in.) or greater in thickness.)

d. Miscellaneous considerations. In general, connections that include tensile stress should be detailed as fatigue resistant details to minimize stress concentration, even if fatigue loading is not present. Under normal operating conditions tainter gates are not subject to fatigue loading; however, fatigue loading may occur due to flow-induced vibration. Using good operating procedures and proper detailing of the gate lip as described in Appendix C can minimize vibration.

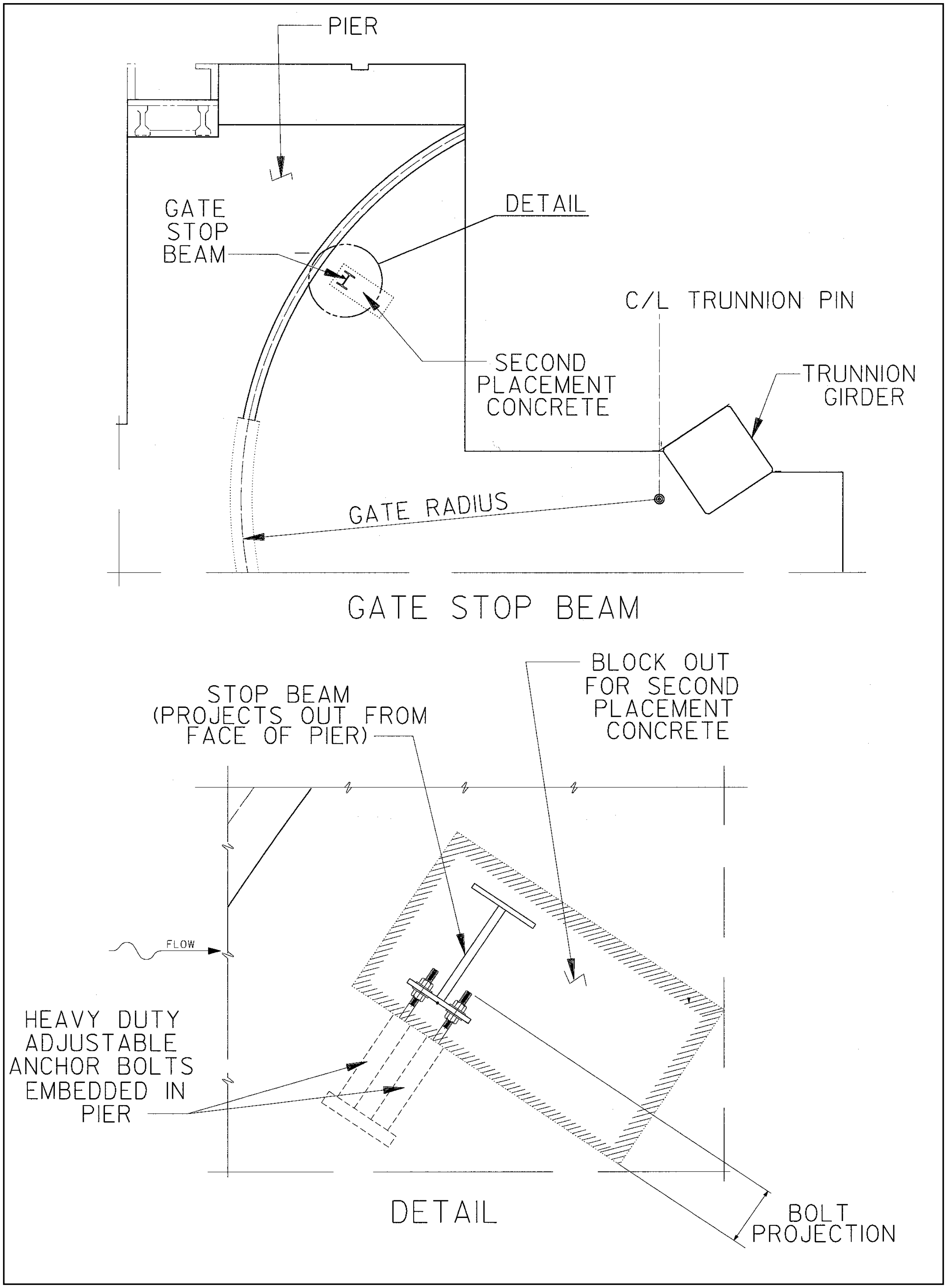


Figure 3-19. Gate stop beam

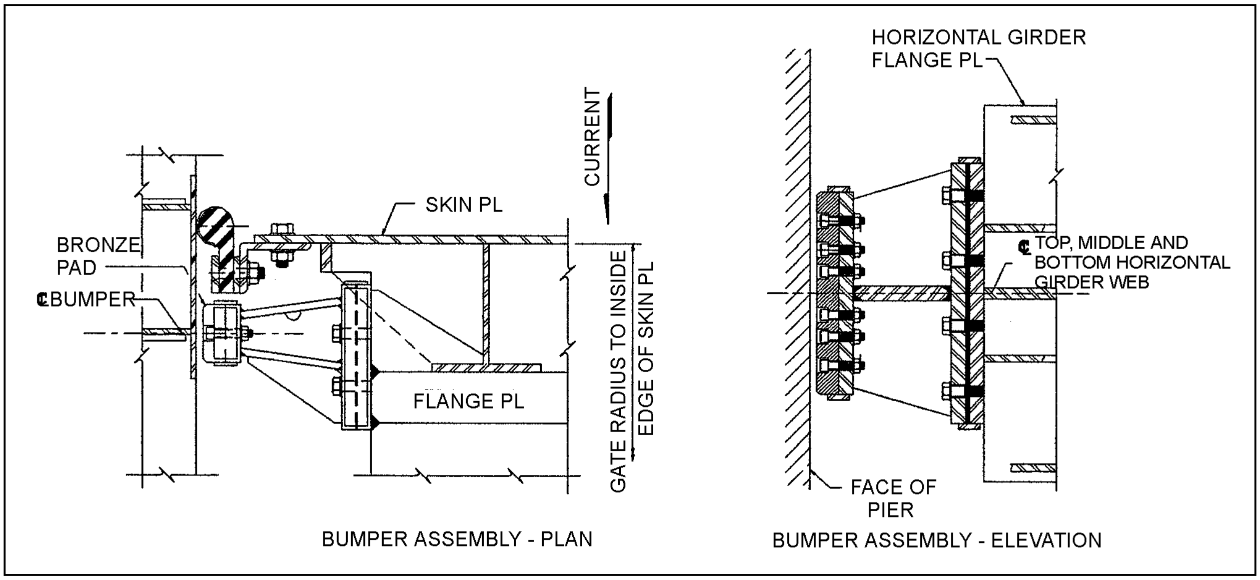


Figure 3-20. Typical gate bumper assembly